Development and validation of a Recycling System Policy for Construction and Demolition Materials

by

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Développement et validation d'une politique du système de recyclage des matériaux de construction et de démolition

Itad Eissa SHIBOUB

RÉSUMÉ

Cette thèse aborde le manque de gestion adéquate de matériaux valables connus sous le nom de déchets de construction et de démolition (DCD) dans les pays en développement. Cette appellation fait référence au béton, à la brique, à l'asphalte, au gravier et au sable anguleux. Ces matériaux sont considérés comme des déchets et souvent, voire toujours dans les pays en développement, éliminés dans des sites de décharge, indépendamment du fait qu'ils pourraient être entièrement ou partiellement récupérés ou recyclés dans de nouveaux projets de construction, économisant ainsi des ressources précieuses, rares et non renouvelables. En plus de l'épuisement des ressources naturelles, l'élimination des déchets de construction et de démolition provoque un engorgement important des sites de décharge avec des impacts sociaux et environnementaux sévères associés. C'est dans ce contexte que cette thèse vise notamment à : identifier et caractériser les déchets de construction et de démolition en Libye et en Tunisie comme étant deux échantillons de pays en développement ; développer et valider une stratégie de recyclage de base appelée Échange-Matériaux-Vierges-Contre-Matériaux-Usagés (V4UX), proposer des avenues à considérer pour inciter les parties prenantes du secteur de la construction des pays en développement à y recourir; et enfin réaliser une intervention routière écologiquement et économiquement durable en utilisant des déchets de construction et de démolition recyclés.

La simulation par la dynamique des systèmes (DS) est la principale approche méthodologique utilisée compte tenu de sa polyvalence pour définir et analyser des systèmes dynamiques complexes à l'aide de modèles informatiques qui incluent à la fois des variables qualitatives et quantitatives. Trois modèles ont ainsi été créés, chacun répondant à un objectif distinct de cette recherche. Le premier modèle décrit et analyse la composition et les caractéristiques des déchets de construction et démolition produits annuellement en Libye en fonction principalement de la production et de la consommation de ciment, de la population ainsi que de la croissance et du produit intérieur brut (PIB) de ce pays. Le deuxième modèle établit un modèle initial de structure de recyclage des déchets de construction et démolition dans une étude de cas du secteur de la construction à Nalut, en Libye. Les économies de coûts et la commodité de l'utilisation de la structure de recyclage motivent la participation des parties prenantes. Le troisième modèle prédit la dégradation future d'une chaussée recyclée en fonction des caractéristiques et de la composition des déchets de construction et démolition et est validé sur des routes réhabilitées dans le port de Radès en Tunisie.

Les conclusions de cette recherche se situent à trois niveaux. Etant difficile de déterminer la quantité exacte de déchets de construction et de démolition, et étant facile de l'estimer plutôt, cette étude a identifié des paramètres appropriés et pertinents pouvant décrire et examiner adéquatement les quantités générées de déchets de construction et de démolition sur des bases rationnelles. Les économies de coûts sont, pour les parties prenantes, une motivation efficace pour entreprendre le recyclage des déchets de construction et démolition. Par ailleurs, le modèle SD analysant la gestion des déchets de construction et démolition en Libye est validé. Enfin, il ressort que les interventions de réhabilitation durable des routes peuvent recourir avec succès à des matériaux recyclés sans compromettre la qualité de l'infrastructure au niveau technique, encore moins les contraintes économiques de rentabilité ou autres considérations environnementales et sociales d'un projet. La validation globale consiste essentiellement en des analyses de sensibilité et une brève réflexion socio-politique.

Mots-clés : Gestion des Déchets de Construction et de Démolition, Evaluation, Entretien, Réhabilitation ; Changement Climatique, Conditions Economiques et Physiques des Routes ; Durabilité ; Modélisation Dynamique des Systèmes ; Pays en Développement ; Economies Circulaires ; Recyclage ; Production et Consommation De Ciment.

Development and Validation of a Recycling System Policy for Construction and Demolition Materials

Itad Eissa SHIBOUB

ABSTRACT

This thesis addresses the lack of proper management of reusable materials known as Construction and Demolition Waste (CDW) in developing countries. Construction and demolition waste refers to concrete, brick, asphalt, gravel, and angular sand. These materials are currently considered as waste and often, more likely always in developing countries, disposed of in dumping sites. This is regardless of the fact that they may be fully or partially reclaimed or recycled in new construction projects, saving valuable, scarce, and non-renewable resources. In addition to the depletion of natural resources, the disposal of construction and demolition waste causes substantial clogging of disposal sites with associated social and severe environmental impacts. It is in this context that this thesis first identifies and characterizes construction and demolition waste in Libya and Tunisia as two sample developing nations, and then develops and validates a basic recycling strategy called the Virgin-Material-for-Used-Material. The thesis then proposes avenues to consider for incentivizing the construction sector stakeholders, in developing countries, to use it; and finally, it carries out an environmentally and economically sustainable road intervention using recycled construction and demolition waste.

System dynamics simulation is the main methodological approach used considering its versatility to define and analyze complex dynamic systems using computer models that include both qualitative and quantitative variables. Three models were thus created, each addressing a distinct research objective. The first model depicted and analyzed the composition and characteristics of Libya's annual construction and demolition waste production as a function of mainly cement production, cement consumption, population and its growth, and gross domestic product. The second model establishes an initial model of a recycling framework for construction and demolition waste in a case study of the construction sector in Nalut, Libya.

The cost savings and convenience of using the recycling framework tend to motivate stakeholder participation. The third model predicts the future distress of the recycled pavement as a function of the characteristics and composition of the construction and demolition waste and is validated on rehabilitated roads in the Port of Rades in Tunisia.

The findings of the research are threefold. Since it is difficult to determine the exact amount of construction and demolition waste, and it is easy to estimate it instead, this study identified appropriate and relevant parameters that adequately describe and examine construction and demolition waste quantities generated on reasonable grounds. Cost savings are, for stakeholders, an effective motivator for recycling construction and demolition waste. Besides, the system dynamics model analyzing Libyan construction and demolition waste management is validated. It is also observed that sustainable road rehabilitation interventions can employ recycled materials successfully without compromising the technical quality of infrastructure, less so the economic cost-effectiveness and the social impact. Overall validation essentially consists of sensitivity analyses and a brief socio-political analysis.

Keywords: Construction and Demolition Waste Management, Assessment, Maintenance, Rehabilitation; Climate Change, Economic and Physical Conditions of Roads; Sustainability; Dynamic Systems Modeling; Developing Countries; Circular Economies; Recycling; Cement Production and Consumption.

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AADT	Annual average daily traffic
ABG	Average Building Generation
ABM	Agent-based modelling
AC	Asphalt concrete
American	Concrete Pavement Association
ACP	Annual Cement Production
AGDP	Average GDP
AGDPGR	Average GDP Growth Rate
AHP	Analytical hierarchy process
ALB	Average Life of Buildings
APL	Average pavement life
ASCE	American Society of Civil Engineers
AW	Available Waste
ATWGL	Average Time for Waste Going to Landfills
BL	Balancing Loop
CB	Cement in Buildings
CBR	California-Bearing Ratio
CDW	Construction and Demolition Waste
C&DW	Construction and Demolition Waste
CLD	Causal Loop Diagram
CRCP	Continuous reinforced concrete pavement
CIB	Conseil International Bâtiment pour la Recherche l'Etude et la Documentation

CTL	Construction Technology Laboratories, Inc
CW	Construction Waste
DB	Demolition of Buildings
DW	Demand for Waste
DWB	Dhibba-Wazin Border
DYNAMO	Dynamic Models Is A Simulation “Programming” Language
EGIS	Environmental Graphical Information System
ELCC	Environmental life-cycle costing
ERR	Economic rate return
ESG	Environmental, Social and Governance
ESAL	Equivalent single axle load
EST	Environnementale Sound Technologies
ETS	École de Technologie Supérieure
EWR	Effect of the Waste Ratio
FGDPGCP	Fraction of GDP Going to Cement Production
GDP	Gross domestic product
GCI	Global Competitiveness Index
GHG	Greenhouse gases
GIS	Geographic Information System
GUI	Graphical user interface
HMA	Hot-mix asphalt
HP	Hundred percent
IFC	International Finance Corporation

INTEG	Rate, Initial Value Numerical Integration
IRI	International Roughness Index
IWA	Initial Waste Available
LCA	Life-cycle assessment
LCC	Life-Cycle Cost
LCCA	Life-Cycle Cost Analysis
LDW	Waste in landfills
L-DW	Landfill-Designated Waste
MAR	Monthly Average Rain
MAT	Monthly Average Temperature
MAX	Maximum
MCDM	Multi-Criteria Decision-Making
MCA	Multi-criteria analysis
MCC	Millennium Challenge Corporation
MCSDE	Monte Carlo Simulation Discret Event
MDD	Maximum Dry Density
MEHAT	Ministère de l'Équipement, de l'Habitat et de l'Aménagement du Territoire
MENA	Middle East/North Africa
MFA	Material flow analysis
MSE	Mean square error
MSW	Municipal solid waste
NIMBY	Not in My Backyard

NCAGDP	Net Change in Average GDP
NCB	New Construction of Buildings
NPV	Net present value
NWGDR	New Waste Generation from Different Resources
O&M	Operations and maintenance
PCA	Portland Cement Association
PI	Plasticity index
PIB	Produit Interieur Brut
PLE	Personal Learning
PMS	Pavement management systems
RBP	Reference Behavior Patterns
RCC	Roller-Compacted Concrete
RDW	Road demolition waste
RL	Reinforcing Loop
RLZ	Radès Logistics Zone
RM	Recycled materials
RMSE	Root mean square error
RRP	Radès Road Port
RS Means	Robert Snow Means Data- meticulous construction costs
RWAI	Ratio of Waste Available to Initial
SD	System Dynamics
SDG	Sustainable Development Goals
SDM	System dynamics modeling

SFD	Stock-Flow Diagram
STUDI	The Tunisian Engineering Company
SusD	Sustainable development
SWM	Solid waste management
OAP	Optimal Average Percentage
TEU	Twenty-foot equivalent units
TRA	Tunisian Road Administration
UC	Unequal covariation
US	United States
VM	Virgin materials
VPDAM	VIZIR pavement distress assessment method
VENSIM	Environment Simulation Software Developed by Ventana Systems
VIZIR	Method for Evaluation Roads Damage
WSP	Williams Sale Partnership
WM	Waste Management
WL	Waste in Landfills
WRR	Waste-to-Roads Recycling

INTRODUCTION

Rapid population growth in the world today is accompanied by comparable industrialization growth to the point that, as living standards increase, the development of the built environment has started to threaten the natural environment (Akadiri 2011). Construction projects are therefore closely linked, and this relationship has received a lot of attention and new scientific research. If not or improperly regulated, construction, maintenance, rehabilitation, and demolition waste from infrastructure development can significantly impact the environment, energy, and material consumption (Marzouk and Azab 2014).

According to Dahlbo et al. (2015), two principal obstacles for CDW are the low cost and high availability of raw materials. Duran et al. (2006) outlined certain preconditions necessary before this situation changes. One precondition is that the cost of putting CDW in a landfill should be higher than bringing the same CDW to a recycling center. A second factor is that raw virgin materials (VM) costs should be higher than similar recycled materials (RM). For example, in roadworks, the cost of primary aggregates should be higher than the cost of recycled aggregates.

These factors rely on the demolished materials' properties and how they have been mechanically treated (Huang, Lin, Chang, & Lin, 2002; Tam & Tam, 2006). Specific to the case of roadwork, most recycled CDW is used as low-cost aggregate in new construction projects or as an element in producing building materials, such as brick and cement. For this purpose, many studies confirm that such recycling is a reasonable substitute for natural raw virgin aggregates (Almadwi and Assaf 2021; Calvo, Varela-Candamio, and Novo-Corti 2014; Fallah-Fini et al. 2010, 2015; Guevara, Garvin, and Ghaffarzadegan 2017; Mohammadinia et al. 2017; Ruiz and Guevara 2020b, 2020a).

These aforementioned factors lower the market demand for RM and limit interest in businesses that may want to focus on it. One option for governments is to use taxation to raise raw material market prices to reduce, eliminate, or invert the market advantages concerning RM. Another government strategy could be to set specific end-of-life criteria for some CDW, increasing the viability of a secondary raw materials market (Galán et al. 2019; Hjelmar et al. 2016; Neuwahl et al. 2019; Santos and Tubino 2021). For instance, Finland used to fall short of the average European recycling target of 47%. As of 2016, to create incentives for projects to recycle CDW, Finland has restricted the disposal of organic waste in landfills. This new regulation may create more demand for other ways of using waste plastics and wood in particular (Dahlbo et al. 2015).

In the future, the need for reusing CDW should increase because aging structures will reach the end of their useful lives and require major rehabilitation (Boateng 2017). How these new factors will affect the CDW composition is unknown. Particular questions pertain to how these factors will affect targets or if substantial reforms to the system must be undertaken.

According to Marzouk and Azab (2014), there is still a greater waste management problem in developing countries (e.g., Egypt, Tunisia, and Libya), where very large amounts of waste must be processed. Currently, developing countries have no systematic means of recycling it, and most waste is disposed of either legally or illegally and not processed or recycled. This process results in serious future economic consequences. For instance, all the money allocated to the problem is used to put the waste in a landfill and to minimize the problems associated with it. The most significant of these problems contribute to growing sustainability issues, including:

1. Depletion of sources of building materials.
2. Shrinking space available for landfills.
3. Environmental damage.
4. Increased energy consumption for VM manufacturing.
5. Contamination from landfill leakage into the soil and off-gassing into the atmosphere.

These issues are compounded because environmental sustainability is seldom seen as being equally significant as technical solutions for infrastructural problems and economic issues.

Conventional management of CDW does not successfully integrate sustainability concerns into the diagnosis of road deterioration and implementation of rehabilitation initiatives. When successfully integrating sustainability into infrastructural projects, there is a greater return on initial investments, given that sustainable solutions ensure improved road performance and longevity.

Poon (2007) outlines some drawbacks regarding the use of recycled CDW. For example, even in the case of aggregate for road construction, it has to be sifted out of demolition materials to be reused. Additionally, care must be taken so that other CDW materials do not contaminate it. Because of this need for separation, a lot of material that could be recycled is instead disposed of via legal and illegal dumping. More and more countries are introducing policies and legislation that directly address the recycling of aggregates and other CDW.

There is a large and noticeable expansion in building construction in Libya (Ali 2018; Elzahari, Ben Zara, & Ghrooda 2013; Salah and Bloomer 2014; World Bank Group 2020). In addition, there are a great number of maintenance projects. Therefore, the design and selection of materials for the rehabilitation of this aging infrastructure has to be of high quality, which in turn means that a strong and convincing case will have to be made to demonstrate that recycling CDW is equally valid on technical grounds, less expensive on economic grounds, environmentally commendable and socially appreciated. This expansion makes some stakeholders and authorities think about the objectives of the construction industry using a sustainable approach. In Libya, the last decade has seen various construction practices without suitable planning or promotion, which are not sustainable construction environments (OECD 2016; Salah and Bloomer 2014; World Bank Group 2020).

To create such sustainable construction environments, initiatives must encourage or even regulate sustainable development (Ali and Ezeah 2017). Many developing regions, particularly Africa, suffer from a lack of suitable materials for public works projects. Road construction, for example, lacks a good supply of gravel and angular sand. At the same time, huge amounts of materials are generated from demolition and are not reused. This process has two consequences. The first is the clogging of disposal sites, where the environmentally damaging effect of the waste represents a liability. The second is the loss of the potential value of the waste material by not reusing it.

The general unwillingness to accept second-hand or recycled materials creates a lower market demand for them. Therefore, the overarching goal of this thesis is to develop a sustainable model of waste management that is appropriate to the social and physical environments and the economy of developing countries, such as Libya and Tunisia.

The two main research questions of this study include:

1) What is the best reason, method, and time to intervene in the CDW life-cycle in the context of pavement management systems?
2) Which decisions of policymakers/stakeholders best address sustainable CDW management needs?

Ultimately, the present study demonstrates that recycling construction and demolition materials helps pavement management in various ways. For instance, it increases average pavement life and reduces pressure on landfills, overall costs, waste removal demand, and the environmental footprint.

During the design stage of building projects, stakeholders must holistically incorporate the four sustainability principles—economic, environmental, technical, and social performance—into the material selection decision-making process. There is much research related to this area (Akadiri 2011; 2012; 2013; Rahla, Mateus, and Bragança 2021), but there are still many obstacles to incorporating sustainability concerns into material selection to make the appropriate decision.

CHAPITRE 1

RESEARCH FOCUS AND OBJECTIVES

1.1 General problem definition

Construction and Demolition Waste (CDW)W is difficult to calculate, but it is very easy to underestimate. For example, the 2012 CDW estimate for Europe (EU-28) was 850 million tons per year (Villoria Sáez and Osmani 2019). This represented about one third of the total waste generation. In the United States, the estimate was 530 million tons. In India, with a population approximately three times the size of the US, it was approximately 530 million tons, according to 2013 estimates (Di Maria et al. 2016).

The European Directive on waste (2008/98/EC) has set targets of at least 70% recycling and reuse of CDW by 2020. In response to this, a great effort has been deployed towards CDW reduction, reuse, recycling, and management. That said, there is a general consensus that the main problems with regards to CDW reduction are material quality and economic viability (Di Maria et al. 2016; Villoria Sáez and Osmani 2019)

1.1.1 Obstacles to sustainable development and reasons against it

Some of the obstacles generally reported against recycling in developing countries such as Libya are:

1) It is not a good time to build waste management facilities for the following reasons:

- Unstable government or support structures.
- Appropriate regulations are not in place.
- There is no collection of waste, community understanding of why it is important to collect waste, or any laws requiring the collection of waste.

- There is community opposition to waste management facilities. The common desire is not to have potentially noisy or smelly facilities close to the public or the people making the decisions, known as NIMBY: not in my backyard.
- Budget limitations to building waste management facilities.
- Lack of space for establishing waste management facilities.
- Immediate environmental costs may be high, even if the long-term costs are lower.

2) Education within the construction industry is lacking, for example:

- Stakeholders do not know the reasons to recycle or the value of demolished material.
- Stakeholders do not know the techniques for building and running a waste management facility.
- Stakeholders and other decision-makers think that used material is garbage and will perform poorly if reused (e.g., reconditioned equipment).

Reasons against sustainable development could be that it will continue to be cheaper to find sources of raw materials and dispose of waste in landfills. Some believe it is cheaper now and will always be cheaper to find new resources and put waste in the landfill. Also, appropriate strategies and systems for the management of CDW are often unavailable. Finally, there are risks. Why bother being innovative and risk failure and disgrace? This is common in many areas and is referred to as the institutional barriers to change (Ali 2018; Etriki 2013; OECD 2016; World Bank Group 2020).

1.1.2 Mechanism of material selection and decision-making

Until the 1930s, in developed countries in Europe and North America, the objectives of construction were always to minimize the original cost of construction. Since then, there has been a growing awareness of this approach's disadvantages because the initial project's low cost might directly compete with the operations and rehabilitation costs. For example, a building might be cheap to build but expensive to operate, namely to heat or cool. This example would occur if the design and construction (design-build) firm is not responsible for the project's ongoing operations and maintenance (O&M).

For this reason, there has been a shift in emphasis at the regulatory level in many countries; there is now more focus on the life-cycle costs of the entire project. In financing terms, owners have shifted from the design-build approach towards the design-build-operate approach so that the total life-cycle bill is minimized. Life-cycle Cost Analysis (LCCA) is therefore an important tool in the economics of the process.

Another equally important economic evaluation technique is Life-cycle Costing (LCC), which quantifies all costs such as increased safety, reduced emissions, and other usually intangible costs and benefits. In LCC, the total cost of the product is evaluated with regards to its entire operating life, taking into account the original capital investment, ongoing maintenance and operating direct and indirect costs, and the expenses associated with the eventual disposal of the product. LCC can thus be used for decision-making and is especially useful for selecting between different construction material options (Arpke & Strong, 2006).

While LCCA is useful, it has to be multidimensional and account for environmental and social effects due to the many elements in the interface of human activities and the environment (Akadiri, 2011). It may be difficult to balance out the concerns of all stakeholders. These sustainability issues must therefore include minimizing environmental, economic, and social concerns.

In order to address stakeholder concerns and institutional obstacles, a number of factors must be kept under control. Poon (2007) discusses examples from areas in Hong Kong as well as Mainland China where they must deal with the dramatic limitations of land availability. There, CDW encounters similar obstacles to aggregate reuse that exist in other areas. These problems include: (1) the low cost of landfill disposal, (2) the absence of taxes on cheap virgin raw aggregate, (3) lack of progressive regulations on contractor requirements, (4) lack of education within the construction sector about the application of recycled aggregate, and (5) lack of appropriate strategies and tools for the assessment and analysis of the CDW.

Even in developed countries, such as the UK or Germany, where the level of sensitivity to reuse and knowledge of it are high, there are other obstacles to sustainable development. To take national strategies for sustainability and implementing them at the local, project level is not an easy task, as pointed out by Ding *et al.* (2016). Akadiri (2011) notes that the national-level strategies are only as good as the decision-making that is made at the local level. It is there that the objectives must be defined as specific and practical actions that are doable in a reasonable time frame.

To improve project sustainability, what can be easily controlled is the selection of materials approved as being “sustainable.” According to Waris *et al.* (2014), this selection process may be the easiest way to ensure sustainability in the implementation of construction projects. However, the present study argues that above and beyond material selection, the sustainability of a project lies in the technical assessment methods and economic strategies used to carry it out. This is the reason that analytical and conceptual tools like system dynamics modeling (SDM), VIZIR pavement distress assessment method (VPDAM), economic rate return (ERR), and net present value (NPV) are explored in this study

1.2 Objectives for a sustainable research framework

This research aims to devise a framework and methodology for developing nations to establish a recycling policy for construction materials. This policy is designed from a socially, economically, and environmentally sustainable perspective. Therefore, the specific objectives of this research are:

1) To establish a systems-based methodology for developing countries to identify and characterize existing CDW and estimate the current and future CDW amount at the city and national levels.

2) To identify the key variables influencing CDW management and establish a CDW circular economy system dynamics model for road rehabilitation;
3) To validate the CDW circular economy model for roads on a case study to identify sustainable interventions and to demonstrate the scenarios of the model's policies.

The following section describes the methodology for attaining the above objectives.

1.3 Research plan and methodology

The methodology to achieve the aforementioned research objectives is based on System Dynamics (SD) (Forrester 1961; Sterman 2000). The systems approach is justified because it can address complex technical, economic, environmental, and social inputs, including stakeholder concerns. The flowchart in Figure 1.1 below represents the activities and procedures of the research objectives.

The first part of the thesis is provided in a first journal paper. The paper is structured to explain how the SD model identifies and characterizes existing CDW and estimates the current and future CDW amount at the city and national levels. It describes and justifies the models used and demonstrates their applicability on a case study on a project in Libya.

Various methods are marshaled for achieving this objective, including a literature review, case study, quantitative model design, qualitative model application, and interview and qualitative data analyses. Other methods include strategic program design, the demonstration of variable relationships and scenarios, sensitivity analyses, and model validations. The methods used to attain each research objective are described below, along with their practical outcomes.

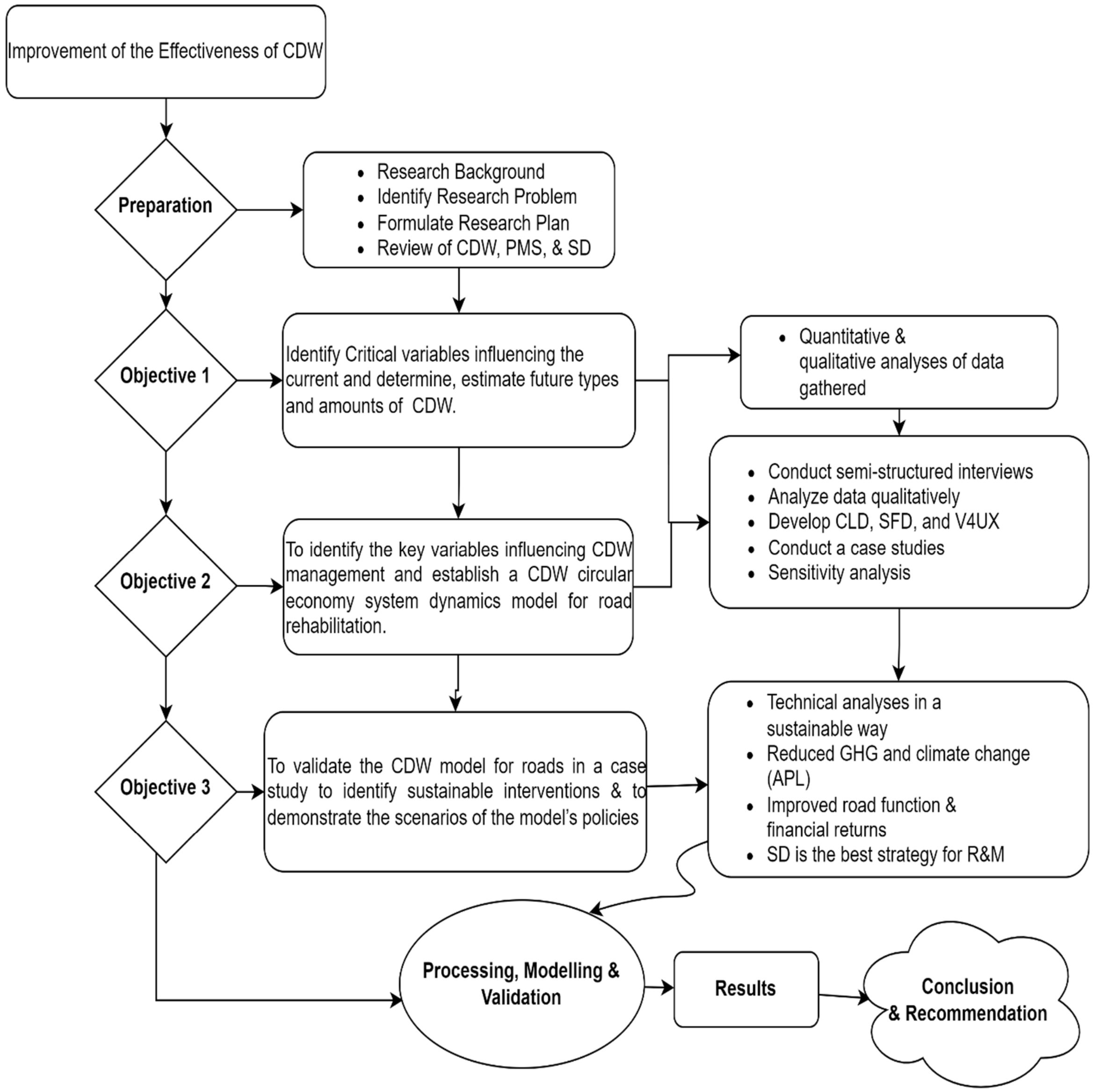


Figure 1-1 Flowchart for the research methodology

Objective 1 is achieved using the following methods:

1) Conduct a thorough literature review of the *Compendex* and *Science Direct* databases.
2) Gather relevant documents, such as government reports from Libya and other developing countries, as well as international aid organization reports.

3) Qualitatively analyze the data gathered from the above documents to estimate the current and future types and amounts of generated CDW.

The outcome of the above procedures was a list of most commonly generated CDW types in Libya, annually estimated amounts, and a series of parameters for CDW assessment used to develop a model for future CDW evaluation.

Objective 2 was achieved using the following steps:

1) Conduct a thorough literature review of the *Compendex* and *Science Direct* databases.
2) Consult government reports, road regulations, and international reports about the state of Libya's infrastructure and economy.
3) Conduct semi-structured interviews with stakeholders of construction projects and government inspectors in Nalut, Libya.
4) Qualitatively analyze interview data to further specify and assign value to the parameters affecting CDW.
5) Generate a cause-and-effect SD model expressing the empirical interrelationships between the main driving parameters related to CDW, including:
   a) developing a novel Causal Loop Diagram (CLD) to illustrate relationships between parameters.
   b) using a Stock-Flow Diagram (SFD) to weigh the parameters affecting CDW and assign each a relative numerical value.
6) Develop a V4UX framework for recycling based on the findings from the above model.
7) Conduct a case study (Libya) to validate the program's effectiveness, the empirical parameter relationships, and the values determined by the SD model.

The outcome of the above procedures was an SD model that can be applied to the analyses of other CDW management systems. Moreover, the V4UX program can be readily adopted by construction sector stakeholders.

Objective 3 was accomplished via the steps described below:

1) Conduct another thorough literature review of the *Compendex and Science Direct* databases.
2) Review and analyze government reports, road regulations, and international reports about the state of the RRP, Tunisia.
3) Conduct a case study involving semi-structured interviews with RRP administrators, qualitatively analyzing interview data to determine current and future road conditions.

The model is shown to be technically sound, based on analysis of the physical road condition system, economic activities, and physical environment. This simulation shows the network effects of the key factors, such as increased greenhouse gas (GHG) emissions and rehabilitation deficits, producing reduced average pavement life (APL) and affecting climate change and the technical principles, resulting in enhanced road function and sustainability and improved financial return.

Objective 4 was accomplished using the following methods:

1) Develop a CLD utilizing the case study's parameters.
2) Use the SFD to weigh the parameters affecting CDW and assign each a relative numerical value.
3) Compare the simulated management scenarios and the results with a base-run for RRP rehabilitation practices at the project level.
4) Evaluate the impacts of climate change on long-term pavement performance.
5) Use the ERR to assess pavement management costs qualitatively.

The outcomes of the above procedures were a validated SD model and a set of recommendations for best strategies for road rehabilitation and related budget allocation.

1.4 Proposed framework

By using SD, this thesis determines the significant parameters that are relevant to CDW and makes their interrelations clear. This process was achieved using published literature, government stakeholder interviews, and data reported by private CDW management experts at the Millennium Challenge Corporation to understand and mathematically formalize the dynamic and time-based relationships contained in the CDW system from generation to reuse. This helps understand and analyze how these parameters dynamically interact with each other. Environmental and social parameters are used to convey those concerns in the CDW system considered by this thesis. The application of SD in this thesis relies on the VENSIM PLE software. This software has a graphical user interface (GUI) that is useful to help the user design and test a system dynamics model.

Most CDW consists of stone, brick, concrete, mortar, and asphalt. However, particularly more recent construction contains materials such as glass, wood, metal, plastic, and contaminants such as silt, silicates, sulfate, chlorides, and organic materials. To identify the amount of waste disposal in the landfill, the study should first identify how much waste is generated. These details are explored in later sections.

1.5 Research significance

This dissertation contributes to the field of CDW management in road rehabilitation and maintenance. Listed below are the subject areas to which the present study contributes.

1) This thesis contributes to the discipline of operations research, including CDW management. The use of SD modeling in combination with a road assessment tool (VIZIR) shows how current and future road performance can be assessed and is a novel way to combine methodologies for this purpose. This research methodology can be built upon by scholars working on efficient assessment and prediction techniques for CDW management.

2) The sustainability pillars that this study develops by adding a fourth (technical) dimension contribute to the broader discipline of environmental engineering since most research in the area only addresses one or two sustainability principles. This elevates the standard for sustainability in engineering according to the 2030 UN Agenda for greater environmental resource conservation and management.
3) Outside of academia, this CDW research can motivate project stakeholders and contractors to work more efficiently, cost-effectively, and sustainably. The simulation of road conditions and interplay of parameters affecting them helps decision-makers accurately assess the current situation and predict possible future performance. This process allows involved stakeholders to make informed financial, technical, and environmental decisions. It can also influence road management and sustainability policy in developing nations (e.g., Libya and Tunisia), especially since their need for cost-effective CDW intervention is so great given the often unstable political and infrastructural context.

1.6 Thesis structure

This thesis is manuscript-based and separated into several sections that are preceded by an introduction. Chapter 1 covers the problem statement, objectives, and outline of the research. Chapter 2 is the literature review, emphasizing the types of CDW prevalent in Libya and how they can be translated into quantifiable SD model parameters. Chapters 3, 4, and 5 identify and introduce major variables affecting the effectiveness of CDW management systems. The variables are mainly concerned with waste generation, and economic, environmental, technical, and social performance as they relate to CDW management. Chapter 3 introduces the SD approach, including its theoretical concept, essential elements for constructing a model, the modeling procedure, and the VENSIM software package used for model simulation. Moreover, these chapters focus on the development of a dynamic model for assessing the effectiveness of CDW management systems. Various CLDs depicting the relationships among key variables are presented, and an SFD is developed. Specifically, Chapters 3, 4, and 5 present the data collected from a construction project in Libya and Tunisia to demonstrate the validity and application of the SD simulation model. They also analyze the simulation results of a series of management policy scenarios.

Chapter 3 is published in the *European Scientific Journal*. Chapter 4 presents an SD model for alternatives in the sustainable management of road demolition waste recycling using a case study of a Libyan roadworks project under the title “Designing a system dynamics model that promotes a circular economy of road demolition waste.” It is under review in the Journal of *Engineering, Construction and Architectural Management* Emerald Publisher.

Chapter 5 demonstrates a dynamic framework for sustainable road infrastructure development and strategies, representing the technical, economic, and environmental aspects using a case study of the Radès Road Port. This paper is published in the *Journal of Management in Engineering, American Society of Civil Engineers* (ASCE). The conclusion and recommendations chapter provide an overall summary of the study, including major conclusions, findings, contributions, limitations, and recommendations for future research. Finally, there are additional materials appended to the end of this dissertation, (e.g. ANNEX I is an additional conference paper associated with the findings of this research especially in Chapter 3, and ANNEX II presents relevant study data and equations used in the models.)

CHAPITRE 2

BACKGROUND AND LITERATURE REVIEW

2.1 Background

Globally, there is an unsustainable yet rising demand for natural resources driven by high consumption in economically developed countries and population increase, and swift industrialization in emerging economies.

Fortunately, companies and countries are increasingly instituting a circular economy approach to address critical environmental and natural resource management issues while generating economic opportunities. This approach is an alternative to the current "take-make-waste" linear economic approach. Traditionally, resources are taken or extracted to make products, later discarded as waste when they stop being useful or wanted. Conversely, circular economies minimize waste and pollution by using resources, materials, and products as long as possible. For example, circular economy approaches may repurpose plastic waste to make new products or use biodegradable waste to produce energy.

The United Nations identifies the three pillars of sustainability as social, economic, and environmental. According to the 2030 UN Agenda for Sustainable Development, there are 17 Sustainable Development Goals (SDGs) to be achieved between 2016 and 2030 (United Nations 2015). Several of these goals motivate this research, starting with sustainable infrastructure, reducing emissions affecting the global climate, and decreasing land and marine degradation. According to the Austrian Academy of Sciences' Institute of Technology Assessment, technological innovation can only happen sustainably if its development starts with sustainability in mind (Austrian Academy of Sciences Institute for Technology Impact Assessment, 2021). Therefore, the current study adds a fourth pillar to consider in the management of construction and demolition waste – the technical dimension, since so much of what makes infrastructure sustainable is how materials are used and their waste is managed.

Sustainability is one of the most important criteria when developing a framework for recycling CDW. Infrastructure in society is an ongoing and growing societal need at the core of the well-being of communities but also one that generates a lot of waste. CDW results from "construction of buildings and civil infrastructure, total or partial demolition of buildings and civil infrastructure, road construction and maintenance" (Environment Commission 2014).

For practical purposes, most CDW consists of stone, brick, concrete, mortar, and asphalt. However, in more recent construction, there are also materials such as glass, wood, metal, plastic, and contaminants such as silt, silicates, sulphate, chlorides, and organic materials (Di Maria, et al., 2016).

2.1.1 Sustainability in the construction sector

Plans for sustainable construction industry development should consider three important concepts:

- Social, to improve quality of life.
- Economic, to provide jobs, improve competitiveness, reduce maintenance costs, and raise productivity.
- Environmental, to minimize the environmental impact of design, construction, demolition, and reclamation practices (Ismam and Ismail 2014).

These concepts apply to any project seeking to increase recycling needs while keeping the feasibility of other environmental and economic impacts in mind. In most cases, waste recycling creates more positive than negative environmental impacts.

In a study of CDW in Spain, Ortiz, et al. (2009) found that the best possible solution was recycling, the moderate solution was energy recovery, and the worst solution was landfilling. Recycling was even preferred when the material had to travel long distances (Dahlbo et al. 2015; Galán et al. 2019; Neuwahl et al. 2019), with the notable exception of heavy materials (e.g., stone).

For the RM to be competitive in quality and cost with VM in the marketplace, Yuan et al. (2011) found that the RM had to be “enhanced.” Such enhancement included separation, sorting, and processing, all of which could raise product costs. Stabilization or improvement of reclaimed CDW may be obtained by adding a binder such as cement or bitumen or lime (Bates and Hills 2015).

In addition, there were ways to decrease costs, such as by creating supporting technologies and using targeted management to increase the efficiency of resource processing, helping to keep costs down (Jia, Liu, and Yan 2018; Wang, Li, and Tam 2015). Therefore, effective CDW project management requires a broad assortment of legal, financial, administrative, planning, and engineering skills.

Studies have recently focused on environmental and economic issues rather than social aspects. This is surprising and will surely change in the near future since younger generations are very active on social media and any incident is immediately reported and viewed by a large number of people. Investors including investment funds are also more socially and environmentally conscious with Environmental, Social and Governance (ESG) ratings assigned to each public corporation which, in turn, justifies higher market multiples over earnings (Bevir 2022). In conjunction with the private investment community, governments in developing countries should also provide tax credits, subsidies and benefits to recycling driven initiatives in the construction industry. Governments in economically advanced countries are currently building frameworks to evaluate the performance of environmentally sustainable building practices. Ismam & Ismail (2014) presented the sustainable construction criteria from an environmental standpoint. The authors suggested developing from sub-issues arising during the construction process towards broader environmental impact issues. Furthermore, the reason for researching and developing sustainable construction management is the lack of scientific waste management frameworks, one of the most significant reasons for researchers and stakeholders to concentrate on.

Shafii & Zahry Othman, (2005) also supported this statement by specifying that the stakeholders faced difficulties dealing with construction waste because of the lack of proven approaches and tools for sustainable construction projects. Thus, addressing challenges at the planning stage of construction projects is important for sustainable development. The three main components that influence decisions in construction are materials, money, and time. Moreover, Akadiri (2011) argued that project sustainability hinges on material and cost conservation and "human adaptation," all of which must be managed throughout the project's life-cycle.

An implementation model for waste management strategies is urgently needed to address the above issues. Agenda 21 of the International Council for Research and Innovation in Building and Construction (CIB) presented a report for construction sustainability, summarizing six important principles to be implemented to accomplish sustainable construction LCA.

2.1.2 Definition of sustainable construction

There are various definitions of sustainable constructions (Holden, Linnerud, and Banister 2014; Plessis 2007; WCED 1987). For instance, Abidin (2010) defines sustainable construction as an approach toward balancing the future needs of development, taking into account a duty to protect the natural environment, establish frameworks for public health, maintain economic security, and develop prosperous places for health, play, and work.

2.1.3 Construction and demolition waste composition

Renovation, construction, and demolition all produce CDW in varying amounts, regardless of the size of the project (from small households to large companies). CDW composition, quality, and amount are not standard from site to site, region to region, or even country to country. There is also no standard makeup of CDW (Neuwahl et al. 2019; Santos and Tubino 2021). For example, a Finnish study showed that, in 2007, there were about two million tons of non-hazardous CDW generated in the following stages: 16% construction; 57% demolition; 27% renovation (EC 2011).

2.1.4 Libyan infrastructural conditions

Private sector development relies on everything from roads, ports, and airports to telecommunications and electrical grids. Such infrastructure must be reliable for the steady delivery of goods and services to markets. Without these, the competitiveness of the country's economy will suffer because of heightened transaction and trade costs. This is especially important for Libya, since it has geographic advantages given its position on the Mediterranean Sea and the need for Egypt and Tunisia to connect by land (OECD 2016).

Prior to the 2011 conflict, Libya already had an infrastructure that had been deteriorating for years. By 2010, decades of isolation and neglect placed the country in the 115th place on a list of 139 countries on the Global Competitiveness Index (GCI) for its overall quality of infrastructure. The 2014 ranking put Libya in the very last (144th) place (see Table 2.1) because, by this time, the road and electrical infrastructure had fallen far behind.

Table 2.1 Road and electrical infrastructure had particularly fallen behind (OECD 2016 p.49)

	GCI 2014-15		GCI 2013-14		GCI 2010-11	
Indicators for Infrastructure pillar	**Value**	**Rank/144**	**Value**	**Rank/148**	**Value**	**Rank/139**
Quality of overall infrastructure (transport, telephony, energy)	1.9	144	2.3	144	3.2	115
Transport infrastructure						
Quality of roads (out of 7)	2.1	142	2.5	134	3.1	97
Quality of port infrastructure (out of 7)	2.6	131	3.0	124	3.2	116
Quality of air transport infrastructure (out of 7)	2.4	139	2.9	136	2.9	133
Electricity and telephony infrastructure						
Mobile phone subscriptions/100 population	165.0	9	148.2	22	77.9	90
Fixed telephone lines/100 population	12.7	82	12.6	85	17.1	74
Quality of electricity supply (reliability) (out of 7)	2.8	116	3.9	96	4.3	81

Over the past five years, the deterioration of Libyan roads limits the country's ability to serve as a transit hub between Chad, Niger and North Africa. Due to this, imported materials are more and more difficult to obtain, just as exports are limited (OECD 2016). Consequently, production levels and associated revenues are down. As of 2012, Libyan government officials projected that US$40 billion should be invested in transport infrastructure alone(OECD 2016; Salah and Bloomer 2014; World Bank Group 2020).

According to the World Bank Group (2020), 80% of stakeholders reported economic losses due to transportation failures. Since then, electric power output has diminished, and the electrical grid has worsened. Even connecting to the grid is a slow process.

Receiving the correct project permits takes 39 days in Tunisia, 64 days in Egypt, and as long as 118 days in Libya, worsening the situation and competitiveness of businesses. The story repeats itself in the telecommunications industry, where, since the 2011 revolution, the US$1 billion communication infrastructure has been damaged or destroyed (OECD 2016).

Libyan construction companies are generally large, meaning that there is ample opportunity and resources to undertake infrastructure improvement projects. However, the work is generally unsustainable, and the infrastructural and institutional barriers make it even more difficult to fulfill sustainability criteria.

Stakeholders ranked each sector according to benefits to the country and other attractiveness factors. Within this framework, the most attractive sectors were the petrochemical, infrastructure and construction sectors. In the OECD Libya meetings in July 2015, there was a discussion and presentation of the sector's competitiveness. From these meetings, five priorities were established: (1) building and construction materials; (2) ICTs; (3) renewable energy; (4) tourism/transit/logistics; and (5) agribusiness, including fisheries opportunities. These sectors will be addressed as the security and political stability of Libya improve. From there, further priorities will be established (OECD 2016).

Table 2.2 Service and industry sector characteristics (2016, p.78)

Sectors/sub-sectors	Sector attractiveness				Country benefits	
	Industry size	Export size	FDI attraction	Labour capital intensity	Alignment with national strategy	Impact on job creation
Services						
ICT	L	L	L	L	M	M
Transit trade (ports, shipping, marine services)	M	M	L	M	M	H
Tourism (and value chain)	L	M	M	M	H	H
Transportation	L	L	M	M	H	M
Education and training	M	L	M	H	H	H
Health services	M	M	H	M	M	M
Financial services	H	L	H	M	H	M
Industry and mining						
Agri-business (including food processing)	M	M	H	M	M	M
Renewable energies	L	M	H	M	M	M
Construction materials and infrastructure	H	L	H	H	M	H
Petrochemicals	H	H	H	M	H	L
Recycling	L	L	M	M	L	M

Regarding the waste management situation, Jalal Etriki (2013) describes the issues that stakeholders face. For instance, the disconnection between stakeholders as coordination and perception are problems between service providers and service users. For instance, "the service providers do not encourage users to be a partner in their waste practices, and the service users refuse to pay for waste service[s] received" (p. 228). Ultimately, stakeholder failures to coordinate and comply with sustainability procedures can result in program collapse. Thus, it is crucial to ensure stakeholder compliance through education and appropriate sustainability infrastructures (e.g., policies, facilities, and motivation tactics).

Furthermore, Etriki, (2013) argues that there is a perpetual lack of funding sources, so reducing construction and rehabilitation costs is always crucial. There is also the concern of continual change in countries' (especially developing ones) political and economic circumstances, in addition to their solid waste management (SWM; e.g., CDW) technologies. Thus, technical, institutional, and operational associations must be dynamic in their intercommunications and approaches to determining and implementing SWM practices.

Moreover, since relationships and needs vary by SWM method, there must also be different policies and procedures that take these dynamic relationships and environments into account (Etriki 2013). Etriki, recommends that countries implement SWM technologies that address one or more of the following conditions:

- Decrease ozone-depleting gases (e.g., GHG) to contribute to worldwide efforts to address climate change.
- Create and ameliorate SWM treatment facilities and efficiency of services.
- Increase and improve resource recovery systems.

2.2 Various techniques for evaluating CDWM

2.2.1 Material flow analysis (MFA)

To estimate the amount and category of materials, the most suitable method that we could use is Material Flow Analysis (MFA), which is a quantitative method used to describe the flow and stocks of a certain material in a system of clearly defined parts. MFA helps us study the effects of human behavior on different scales, including in time and space. It can be used to study an ecosystem, a segment of an industrial process or procedures in a waste management operation including clients and the final processing plant.

MFA describes real world systems having set and variable characteristics including whatever sources, pathways, and sinks affect the material or system. Adhering to the law of conservation of matter, the details of an MFA may be dictated simply by the balance of all inputs, stocks, and outputs as is shown in Figure 2-1. This quality results in a powerful methodology, especially as a tool supporting decision-making for resources, waste and environmental management.

MFA gives a comprehensive and consistent dataset including all movement and reserves of a given material within a system. Balancing inputs and outputs allow the flow of material, including waste and environmental load to be accounted for. As well, data on social or economic aspects needs to be accounted for to manage such systems responsibly.

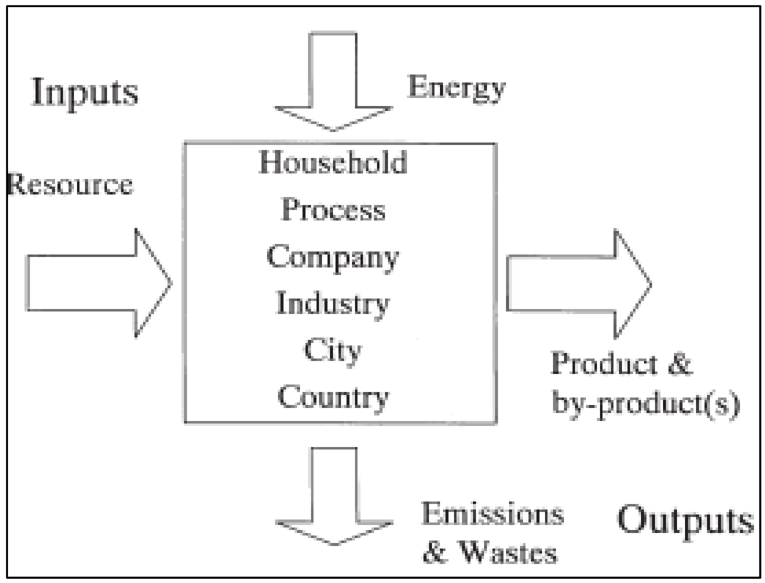


Figure 2-1 Simple outline of MFA
accounting (1999, p.3)

MFA can be used in the absence of these factors, but most of the time, such details are necessary to best use the MFA data. Therefore, MFA is often used with economic, urban planning or energy analyses, as examples. Moriguchi's (1999) paper focuses on recycling and WM from a material flow accounting viewpoint and discusses the waste stream from material stocks.

Moriguchi (1999) notes that it is more important to keep the emphasis on the reduction of inputs of new resources and outputs of waste instead of being overly concerned with the total levels of recycled materials. By combining some tools for decision-making in uncertain situations with multi-criteria analysis (MCA), system dynamics (SD), and agent-based modelling (ABM), we can understand a project better. An example is to take systems like the Geographic Information System (GIS) and simulation systems such as SD or Monte Carlo Simulation Discrete Event (MCSDE) and combine these with different scenarios to assess the

MCA outcomes. This provides greater insight into stochastic uncertainty as it applies to the problem, for example, aspects of the model that are uncertain, data input, etc.

It is important to understand how uncertainty works in each special context, including what degree events and natural features play a role. The management of uncertainty is a key factor for stakeholders in being sure that the decision-making is transparent.

2.2.2 Life-cycle assessment (LCA)

Life-Cycle Assessment (LCA) or Life-Cycle Analysis is a method used to examine a product's environmental impact through every step of its life, starting from the product in a raw material state and following through to factory production, sale to a consumer, use by the consumer and its eventual disposal (Cabeza et al. 2014; SETAC 1993).

The focus on environmental considerations has been around long enough that it has been accepted as mainstream. We now understand that the earth has a finite capacity to balance and absorb the output of human wastes and, ultimately, the earth restricts development. Many areas of the earth have suffered because we have not understood or have not been able to find ways to mitigate our waste output (United Nations 2015).

Taking action to prevent the worst outcomes of our waste production is not an easy task. Sustainability projections and research needs to be followed up by concrete steps if we are serious about reducing environmental impacts and climate change. If such steps are to have an effect, the following factors need to be addressed:
Suitable technology must exist.
Solutions need to be chosen based on cost, efficiency, and economic and social impacts.
All steps need to be made with the objective of reducing further environmental impacts.

In these terms, LCA becomes a tool to help decision-makers keep the essentials of the problem in mind. This analysis is very important especially when the budget is limited. This is described in greater detail by Iacovidou et al. (2017).

The problem is not one of how to tackle the individual problem; the engineering is either available or can be developed to deal with that. Rather, the problem is how to decide priorities. The world just cannot afford to do everything.

LCA helps us use and understand technological innovation because it shows us what priorities to keep in mind. This is especially true from an environmental sustainability point of view because it helps us see products and services in terms of full life cycles and not be distracted by “local” innovations that may do nothing more than displace their environmental footprint somewhere else.

What makes LCA different from other systems of evaluation is that it works by making sure the functional effectiveness of any environmental solution is the most important thing. This means the GHG emissions and raw materials are considered based on their functionality within the system (or within the product).

The history of the method can be traced from Europe and Japan up into the middle of the early 2000s, when it started to be used more and more in North America and countries in the global south. Much of this change was driven by large international corporations wanting to understand the sustainability of their own products including meta-analyses and reviewing the important LCAs on a certain topic (for example, using biomass or solid waste treatment).

Wäger and Hilty (2002) use a System Dynamics model combined with Life-Cycle Analysis (LCA). Here the question arises of how best to integrate simulation methods with more conventional decision-making and planning methodologies; integrating these two areas was, as of 2002, still relatively new. The authors discuss their waste management model in relation to systems that support decision-making. The model simulates the economic and ecological effects of planned developments up to fifteen years in the future, allowing users to configure input variables pertaining to the projected waste stream developments.

Other configurable factors pertained to economic and environmental variables including the amount of waste and overall energy consumption. Their model was suitable as both a general learning tool for how to approach existing waste management issues as well as for exploring potential waste management methods in projects that are being considered for implementation. Ige et al., (2021) used a life-cycle assessment method to evaluate the impacts on the environment of materials used in the production of cement, such as fly ash and blast furnace slag. Other researchers, such as Shen & Tam, (2002), used a mapping technique to analyze waste handling protocols for construction.

2.2.3 Environmental life-cycle costing (ELCC)

Dahlbo et al. (2015) showed that the various factors presented above can be calculated by means of environmental life-cycle costing (ELCC). To determine the full CDW project costs, ELCC can be used. The ELCC can be determined from the point of view of the consumer, community, company or society. ELCC, together with LCA, has become a viable tool for assessing the sustainability of projects (Swarr et al. 2011). ELCC is distinct from the older LCC methods, which focused on economic dimensions of projects, since it also considers ecological factors (Knoeri, Binder, and Althaus 2011; Neuwahl et al. 2019; WCED 2011). Figure 2-2 shows the life-cycle processes, phases and mass flow analysis SE in the ELCC and LCA exported CDW management protocol (Dahlbo et al. 2015, p.336)

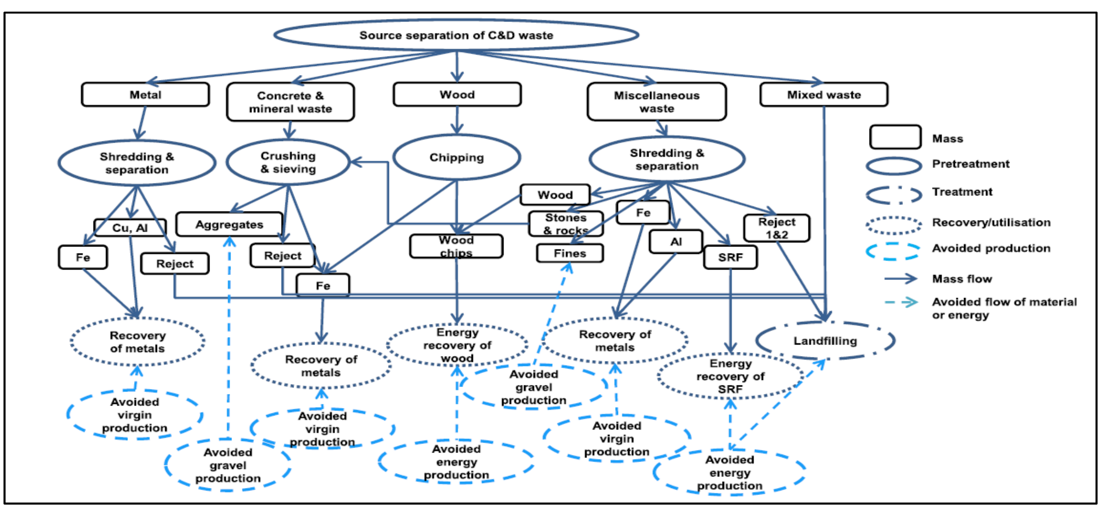


Figure 2-2 Life-cycle processes, phases and mass flow analysis (2015, p.336)

2.3 Using quantitative assessments in decision-making processes

2.3.1 The System dynamics Definition and background

This section reviews the principal tool in this research: system dynamics. The review includes a history of its development, its advantages and its applications in the domain of WM. R. G. Coyle defines system dynamics as “a method of analyzing problems in which time is an important factor, and which involves the study of how a system can be defended against, or made to benefit from, the shocks which fall upon it from the outside world” (1977).

SD is a methodology that uses computer simulations to help in problem solving. SD presupposes a holistic approach to a project and focuses on trends in the behavior found in various management strategies. SD was first developed at MIT in the 1950s by Jay W. Forrester (Hongping 2011). However, SD has relatively recently become much more popular because more powerful computer simulations are possible for the use of SD as a problem-solving methodology. Forrester’s original ideas came about when he applied concepts from theories of feedback control to the domain of industrial systems; he then applied these in the context of urban dynamics. His work has reference in the field of engineering control systems as well as systems related to information feedback theory. Forrester (1968) describes how he used analysis and modelling techniques from control engineering and adapted them into a flexible system that could be used in the social and business domains. He developed a set of symbols to create diagrams that represented and connected systems.

Once computers became more available and more powerful, SD could be used to create quality graphics that allow researchers to map symbols and interact with them on a computer monitor. A great number of practical real-world projects have shown SD to be a useful analytical technique. SD simulation models have many applications, including in civil engineering and policy and strategy assessments. Where SD is particularly useful is in showing interdependencies that have multiple values (Liu 2004).

According to Yuan & Wang (2014), it is particularly useful for understanding systems from a holistic point of view where the interactions of different system elements are important. As Richardson & Otto (2008) point out, it shares the advantage of many modelling approaches, in that it allows the researcher to investigate hypothetical setups and understand how different policies and variables will affect it.

The System Dynamics Society (Barlas, 2015) recently claimed that the factor that makes SD distinct from other projects is that it gives the researcher tools to manage stocks and flows; these describe how feedback loops connect in a project and, in turn, result in non-linearity that is so critical in modern analyses. By using SD models, the researcher can simulate hypotheses and thereby test how various policies can affect a system over time (Knoeri et al. 2011; Sterman 2000).

According to Marzouk & Azab (2014) and Yuan Hongping (2011), the features of SD include:

- SD models may be cross-scalar and modular, whereby the models may be nested in order to attack the problem at various degrees of granularity.
- SD models allow for the use of variables that are both quantitative and qualitative; these variables may be determined on an ordinary scale of low to high, e.g., the case of components in social systems projects.
- In this way, SD models can address multiple project goals.
- SD models allow for greater transparency, ease of adoption and adaptability.
- Because SD models are dynamic and modular, the new user can easily see the effects of their changes and so learn the system quickly. This creates an acceptance of the approach and a sense of trust, a sense of involvement and a stake in the outcome.
- Variables do not need to be established previous to execution; variables can be either dynamically or manually updated.
- Software such as Stella, iThink and VENSIM are available for reasonable prices.
- The results of the simulation can be output in various forms, through graphs and diagrams.
- There are built-in error checking protocols.

- The SD modelling allows for continuous and systematic evaluation of parameters, as well as a way to determine how sensitive the system is to different variables. Restrictions on variables are few so long as the relationships can be defined and identified.
- Assumptions can be easy to control or influence mathematically, as long as the assumptions are clear (explicitly or implicitly). I.e., the problem does not need to be simplified, as long as it can be suitably broken down into discrete steps.
- Through the course of the project, there are means to use the model for team-building, team learning and for establishing consensus among stakeholders.
- SD allows projects to model time-delay and internal feedback loops critical to the behavior of the system.

Key to the above criteria is being able to correlate the behaviors of a system in time with its base decisions, rules and structures. Modelling allows us to consider hypotheticals, testing the effects of a given policy in an empirical way. As Marzouk and Azab (2014) noted, this increases the likelihood that a given policy proposal will be accepted.

There are several general reasons to use SD in the current study:

- Understanding nonlinear critical features that are normally accounted for by reinforced or balanced feedback loops.
- Evaluating the system holistically, as an integrated whole and not just a collection of different elements.
- Working with new analytic tools, given that many traditional tools have been found to have had limited success, especially with regards to the broader context.

The importance of having an adaptable project model is what allows a research group to play with various options (Hongping 2011).

2.3.2 SD application in waste management

Mashayekhi (1993), Sudhir *et al.* (1996), as well as Wäger & Hilty (2002) all report applications in waste management and discuss how it can be used as a complement to more traditional WM techniques. A model using SD is generally based on the factors making up its reference mode and the cause-and-effect relationships that come out of such a study. Before a quantitative simulation can be made, the researcher starts by creating a series of diagrams that show the qualitative influences on the project. Once the qualitative factors are determined, the quantitative model can be developed and it is this model that gives a representation of complex scenarios that is flexible with regards to a number of factors. This model can then simulate behavior patterns over a variety of timescales. The SD model is able to show cause-and-effect relations using stocks and flows, which are the component parts of SD models. Here, stocks (also known as levels) are used to show where the system creates accumulations of materials that will remain after all activities stop.

The accumulations show the system state, and such values are only altered by flows. Information and material flows are the two types of flows that are contained in the feedback loops. The materials that flow in, between, or out of system boundaries are referred to as the material flow or simply "flow." These flows then provide inputs to the model; this information flow can then be used to represent the material flows.

Overall, in a context like waste management, the system behavior relies on many factors. These factors are systemically variable and the feedback within the system must be dynamically and continuously analyzed. The study of the management of municipal solid waste in Pueblo, reported by Marzouk & Azab, (2014), also employed an SD approach. Here the researcher attempted to find a compromise between various well-established techniques in order to resolve the problem with regards to public administration issues.

In the history of SD, a number of software systems have been used. The first of these was DYNAMO and others include STELLA, SIMPAS, and PowerSim. VENSIM is used by many researchers today. The present research uses VENSIM PLE. Some of the advantages of this software application are that it has a graphical user interface (GUI) that is useful in the significant stages of development from the conceptualization, building and testing stages of an SD model.

Research into WM often uses SD simulation. Bala *et al.* (2017) used SD modelling to calculate the approximate volume of solid waste in Dhaka, Bangladesh; they also calculated the collection capacity as well as the capacity for electricity generation pertaining to this waste. An SD model was also used by Kollikkathara *et al.* (2010) to understand the interrelations among the three central factors of solid waste generation, landfill allowance, and economic impact. SD analysis gave important insights on the management of urban waste.

SD modelling was also used by Yuan et al., (2011) to evaluate the cost-benefit factors in CDW management in Shenzhen, China. Based on the results of that study, there is a net benefit for CDW management that comes from imposing a surcharge on landfill use, particularly if it is implemented early in the process. Nonetheless, there is a risk that a higher landfill charge will increase cases of illegal waste disposal. Therefore, these benefits will not be seen without an accompanying enforcement of local waste management regulations.

Doan & Chinda (2016) give a number of rationales for choosing SD simulations in research that studies the practical application of a CDW recycling system. SD modelling can accommodate dynamic changes in a system (changes that cause other changes in the system); help in the analysis of cause-and-effect between factors, e.g., between costs and benefits in the CDW recycling system; and test alternative plans to pick the most practical choice.

Doan & Chinda, (2016) also outline certain shortcomings of an SD approach. These include possible problems when the method is used at extremely detailed levels. This is a limitation of the computers used for the modelling because there are many complex mathematical equations that must be returned. This limitation is perhaps mostly theoretical at this point but could have been a greater obstacle even twenty years ago. The other main difficulty of SD modelling is in determining the system boundaries; this involves a qualitative judgment of what factors are best to include or exclude from the model. However, SD techniques create a good foundation for evaluating the interconnections among important elements that can impact the implementation of CDW recycling programs.

Nonetheless, a lot of research in WM does not use SD modelling. Some researchers use methodologies with a fuzzy approach. An example of this is the work of Nasiri & Huang, (2008), where they created a methodological analysis of waste recycling. Others, such as Chang & Wei, (2000), have used fuzzy multi-objective nonlinear integer programming simulations in order to determine the best siting and routing choices for a solid waste collection system

2.3.2.1 SD in developing and developed countries

In the last twenty years, more and more studies have applied system dynamics to CDW management as illustrated above. Sudhir et al., (1996) created a systematic simulation model targeting the planning stages of municipal solid waste (MSW) recycling management systems. Their model used system dynamics and data from developing countries. With the model, they were able to analyze a number of issues, including the following: environmental factors, public health, costs to society (present and projected) and the effect of various groups who played an informal role in the recycling system. For the model, the management systems fall into three sub-systems. These encompassed waste generation, and formal and informal recycling areas.
They noted a very large distinction between how the waste was processed when comparing developing and developed countries. Of special note was that in developing countries there was a sizeable *informal* waste processing system including itinerant buyers of waste, waste gatherers, scrap dealers and waste wholesalers. These were useful indicators allowing the authors to analyze the policies pertaining to waste management. Formal systems also existed and were more similar to systems found in developed countries. These depended on local government budgets and included collecting, transporting and disposing of waste. The study compared two management policies that used different allocations of funds and methods of evaluating the waste management; these were then used to check the model.

Mashayekhi, (1993) developed a quantitative system dynamics model to evaluate solid waste issues in the state of New York; this was then applied to various policies that could be considered by the government for adoption. This model put more emphasis on internal system financial matters due to the fact that a number of landfills had closed, and there were greater costs associated with educating the public in these matters.

In the New York area, there was a shortage of appropriate locations for new landfills and, with it, a steeper cost associated with the development of new sites; both of these factors meant that governments would have to spend more on solid waste than previously. In the model, they distinguished a number of subsections including budget allocations, waste generation and, finally, waste stream allocation. They then considered four policy alternatives and evaluated them according to the influence of waste disposal and how it might improve the existing processing systems. The model then helped determine the most cost-effective option.

To evaluate the effect of management options for reducing CDW, Yuan et al. (2011) created a system dynamics simulation. In order to analyze the effects of waste generation, illegal dumping, transport, recycling or landfilling, Tam et al. (2014) built a system dynamic simulation, finding that better execution of government policy on legal and illegal dumping was able to curb illegal activity and sizably reduce construction waste. Yuan et al. (2011) cited a great number of earlier studies suggesting the potential of system dynamics, and Yuan & Wang (2014) implemented a system dynamics model to analyze the effects of a construction waste (CW) disposal fee.

Ding et al. (2016) discuss how system dynamics models have been used in ecological, social, business, economic, and agricultural studies and these have appeared in a number of academic publications. An example is the economic and environmental disposal of CDW reported in China (Ding et al. 2016). Likewise, Hao et al. (2008) used a system dynamics model for analysis of construction waste in Hong Kong in order to improve decision-making by helping stakeholders plan and understand the complexity of construction waste flow throughout the life-cycle of a project. Ding et al. (2016) used system dynamics models to illustrate that one of the most efficient means to reduce construction waste is reduction of waste sources, which provides great environmental advantages. By targeting reduction at source, Ding et al. (2016) reported that projects can reduce construction wastes by up to 27.05% and pressure on landfills by approximately 53.77%, thereby reducing fertilizers, water loss and conserving other land resources. Ding's (2016) model indicated that sorting tendencies ensure greater recycling and reuse of construction waste. These prompted people involved in construction to initiate sorting at source that had positive effects on the recycling totals and netted a number of environmental advantages.

Ding's (2016) conclusions pointed to the fact that there is interest in decreasing environmental impacts by reducing construction waste. As reduction at source becomes a priority and the environmental advantages become more evident, it will be seen as an advantage over sorting strategies. At this point, technologies that help reduce waste will be more readily adopted in order to improve environmental performance of construction waste reduction programs. Until that happens, it is a priority to increase the awareness of stakeholders, improve government supervision and fine-tune the regulations governing the industry. At the same time as the legal means of construction waste reduction are improved, so too must illegal alternatives such as illegal dumping be controlled. Following these principles, a model is developed in this study.

This study used average income based on economic activity, population, and cement production and consumption to distinguish the sources of waste generation in Chapter 3. Chapter 4 introduces institutional barriers to recycling and explores ways to incentivize stakeholders to recycle by establishing a V4UX strategy. Chapter 5 discusses the three pillars of sustainability (economic, environmental, social) and proposes the addition of a fourth (technical) in the context of sustainable pavement management.

2.3.3 Causal loop diagram

In a Causal Loop Diagram, a loop is either Reinforcing or Balancing (also expressed in the literature respectively as Positive and Negative). A Reinforcing Loop (RL) has no apparent limit to the number of loop cycles. On a broad enough timescale, generally, this hypothetical situation will be contradicted or contained by a Balancing Loop (BL). Figure 2-3 shows the complete CLD, including reinforcing feedback loops (RLs) and balancing feedback loops (BLs). Table 2.3 provides a list of symbols used in the CLD**.** Service Allowance Compensation for Waste Collection is a BL because the service of the stakeholder participation counters the service of government collection; likewise, V4UX is a government service providing recycled materials at a reduced price in return for the used recyclables.

In the first stage, the reinforcing loops are not self-sustaining because V4UX requires the government to invest in the cost of collection and recycling. However, in the long-term, the government should see higher tax revenues due to increased trade and other economic development. Local trade also becomes more efficient in an economy not having to contend with corruption (Anon 2019a; Wef 2013); international trade, the key to the local area under study, can also be expected to rise (OECD 2016; Wef 2013). Although collecting tax money from local trade is outside of the scope of this study (and not a factor that can be depended on (Ali 2018; Anon 2019b; Etriki 2013; Peterson 2017), revenue from international trade is easily collected at border points (Peterson 2017). This money can be directed back into V4UX. This is to say, when international trade rises, it creates an RL that funds V4UX**.** It is important to note that after each completed cycle, the "lifespan" of the feedback loop diminishes due to increased uncertainty. Over time, the likelihood of disruptions increases and the loop ceases to function.

The objectives of having both a cleaner environment and less institutional corruption in the near term have important economic benefits; these objectives can be best met with V4UX. The first stage of this proposal involves achievable, local objectives, starting with a government road waste collection initiative. The **RDW** is collected from contractors by government collection agents; government-paid facilities then recycle it into material that can be sold back to contractors for a price that is competitive with VM. In the long-term phase of the project, that same road, constructed from recycled RDW, will need to undergo the same process, perhaps in a twenty to thirty-year cycle. This cycle, while Reinforcing in principle, needs a regular influx of government capital to underwrite the financial needs of these recycling programs. Furthermore, there is the question of "downcycling" whereby a given material is recycled into a slightly downgraded material and may need a certain amount of VM to provide a quality consistent with 100% VM (European Commission, 2016). For these reasons, a larger view must be taken. If the above goals are attained, the system will naturally help create a lower incident of corruption and, therefore, systemic efficiency. The knock-on effects include increased trade and a cleaner environment.

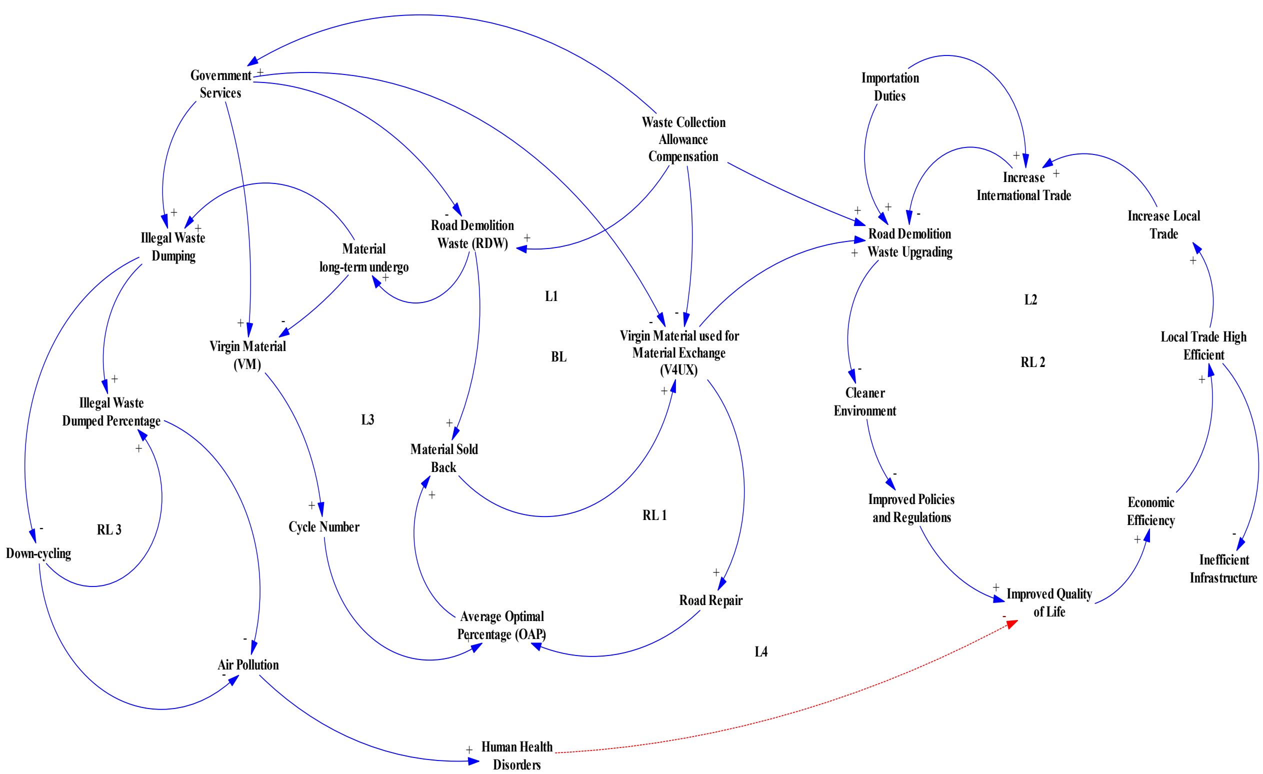


Figure 2-3 Complete Causal Loop Diagram (CLD)

Table 2.3 Symbols list of the CLD 2.1

• **Increased RM**	**IRM**
• **Reduced VM**	RVM
• **Increased Return of Used Recyclables**	IRUR
• **Increased Rate of Service Allowance Compensation**	IRSAC
• **Increased Collection of RDW**	ICRDW
• **Improved RDW Legislation**	IRDWL
• **Reduced Illegally Dumped Road Waste**	RIDRW
• **Reduced Delay of Road Rehabilitation**	RDRR
• **Increased RDW Material Sold Back**	IRDWMSB
• **Improved Policies and Regulations**	IPR
• **Increased Local Trade**	ILT
• **Increased International Trade**	IIT
• **Increased Tax Collection**	ITC
• **Increased Initial Infrastructure Investment Costs**	IIIIC
• **Reduced Environmental Footprint)**	REF
• **Reduced Ongoing Infrastructure Costs**	ROIIC
• **Increased Recycled RDW**	IRRDW
• **Increased Material Life Span**	IMLS
• **Increased Cycle Number**	ICN
• **Optimal Average Percent**	OAP

<u>Loop 1</u> (L1) describes RDW-U:

IF L1 is Reinforcing for the *number of cycles* (n) ELSE each cycle, it degrades by *x*%, then *y*% VM is needed THEN L1 becomes Balancing at *w number of cycles*.

In practice, it is optimal to add a certain percentage of VM to the mix; therefore, the calculation for the maximum number of cycles that the recycled materials could, in theory, be used for is, in practice, extended by the need for a stronger road structure. Therefore, instead of trying to maximize the number of cycles without any VM, it is necessary to find the Optimal Average Percentage (OAP) of VM to be added to a project largely focused on using recycled materials. With that OAP, we can then determine how best to manage the virgin natural resources as well as the recycled materials represented in L1**.**

For the simplicity of the initial model, L1 is examined in its early cycles, and the discussion ignores cycling degradation. As such, in the initial stages, L1 is a reinforcing loop. Figure 2-4 shows a reinforcing feedback loop (RL) and a balancing feedback loop (BL) where RDW-U is feeding the V4UX strategy. Loop 2 (L2) shows how improving the infrastructure can help increase trade and how increased trade can help regulation, etc. There is an important connection between the infrastructure, the environment, and trade. Inefficient infrastructure discourages international trade and hampers local trade (Environment Commission, 2014; 2016). Strong international trade, in turn, helps fund the government through import duties (Christian 2017). When the government has a very small working budget, it cannot enforce regulations, including regulations that protect the environment and, consequently, human health(Calvo et al. 2014; Nwachukwu, Ronald, and Feng 2017).

Trade is affected when human health suffers (Frenk 2004). Therefore, in the broadest terms, L2 is a reinforcing loop. This is not to overstate the value of V4UX but to indicate that it could play a small but important step in helping a country like Libya develop sustainably in the long-term. Specifically, unregulated vehicles running over poorly maintained road surfaces often have a much higher rate of pollution in terms of fine particulate matter and oxides compared to vehicles that are more tightly regulated running on better road surfaces. The fine particulate matter is the most harmful. It is measured in terms of “PM 2.5” levels; PM 2.5 refers to airborne particulate matter, especially as it affects human health and is related to lung disorders, cardiovascular diseases, neurological disorders, and reproductive disorders; one study estimated that each year, 48,000 deaths in France were related to airborne particulate matter, which is equivalent to 9% of the total deaths in France (Pascal et al., 2016). Given that countries like Libya generally have worse air pollution in highly populated urban centers than a country like France, it can be estimated that the health impacts are also worse.

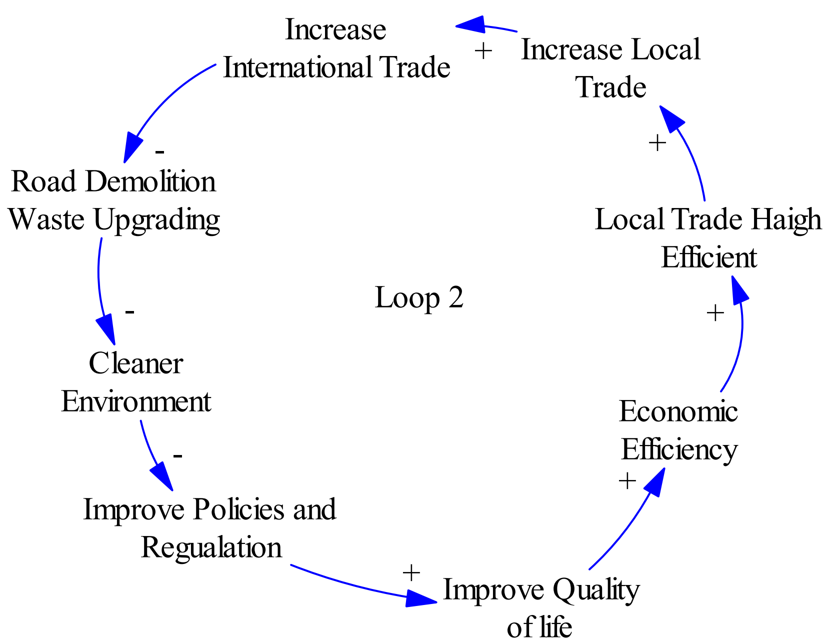


Figure 2-4 Example of Loop 1 isolated

<u>Loop 3</u> (L3) addresses the **downcycling** problem, illustrating that L1 is not perfectly reinforcing. Each time the materials are recycled, they must have a small proportion of VM added to bring them up to the level of quality for a project relying wholly on VM. Although this could be incorporated into L1 analysis, for presentation purposes, it is useful to see L1 as a broad outline of the possibilities of the project without secondary details.

<u>Loop 4</u> (L4), like L3, examines to what degree **L2** is perfectly sustainable; it must be considered whether or not the benefit in improved infrastructure and the consequent environmental improvements, with the related better trade and human health benefits, justify the cost of the initial infrastructure investment. In this analysis, international trade is recognized as a variable that could collapse due to changes in the price of oil, a military conflict, or global warming, etc. Likewise, the balance between the money raised by import duties may or may not adequately fund the cost of infrastructure development; there is a limit to how high import duties can be before they negatively affect trade.

2.3.4 Stock-flow diagram (SFD)

SD simulations are made up of four parts: stock (i.e., reservoir, level, or state variables); flow (i.e., control variable, rate, processes); connector (i.e., information arrow); converter (i.e., translation variable or auxiliary). The model itself is made up of nonlinear differential equations pertaining to the state, flow, level, auxiliary, conditions, parameters, and initial values. Figure 2-5 shows the simplified SFD. The level equation presents the system's dynamic behavior and can be represented as in Eq. 1 and Eq. 2:

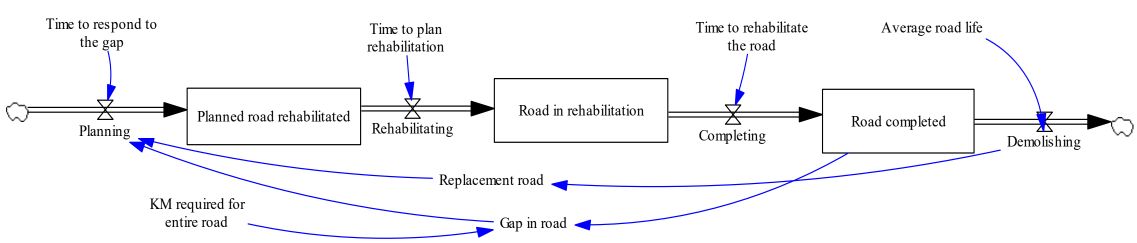


Figure 2-5 Simplified Stock-Flow Diagram (SFD)

Eq. 1) $\frac{dXi(t)}{dt} = f(Xi, Ri, Ai, Ci)$

The differential equation itself is:

Eq. 2) $Xi(t + \Delta t) = Xi(t) + f(Xi, Ri, Ai, Ci) * \Delta t$

Where Xi(t) is a state variable vector; f () is a function of vector values; Ri is a flow variable vector; Ai is an auxiliary variable vector; Ci is a parameter vector; t is a variable of time; Δt is change over time. These can be solved numerically by simulations with the Euler software. State equations (Eq. 1 and Eq. 2) express time as either past, present, or future; the present sums past states, as well as the difference between the present and the past period; the future state expresses the present state plus the time period variation. As such, this describes the variations found in the system over time.

The Vensim software was used to model the Stock-Flow Diagrams (SFD). These SFDs illustrate the various policies that contribute to V4UX, including RDW-U; RDW-U itself is a V4UX. The principal variables are shown in Figure 2-3. The V4UX will be described in greater detail in Chapter 4.

2.3.4.1 Example of input to the SD model

Flow material in CDW management contains several steps, as shown in Figure 2-6 (e.g., waste generation, sorting, recycling and reusing, illegal or unregulated dumping, landfilling). The complexity and dynamic system of managing CDW at the construction stage include (1) government regulations and policies, (2) budgets, and (3) environmental benefits.

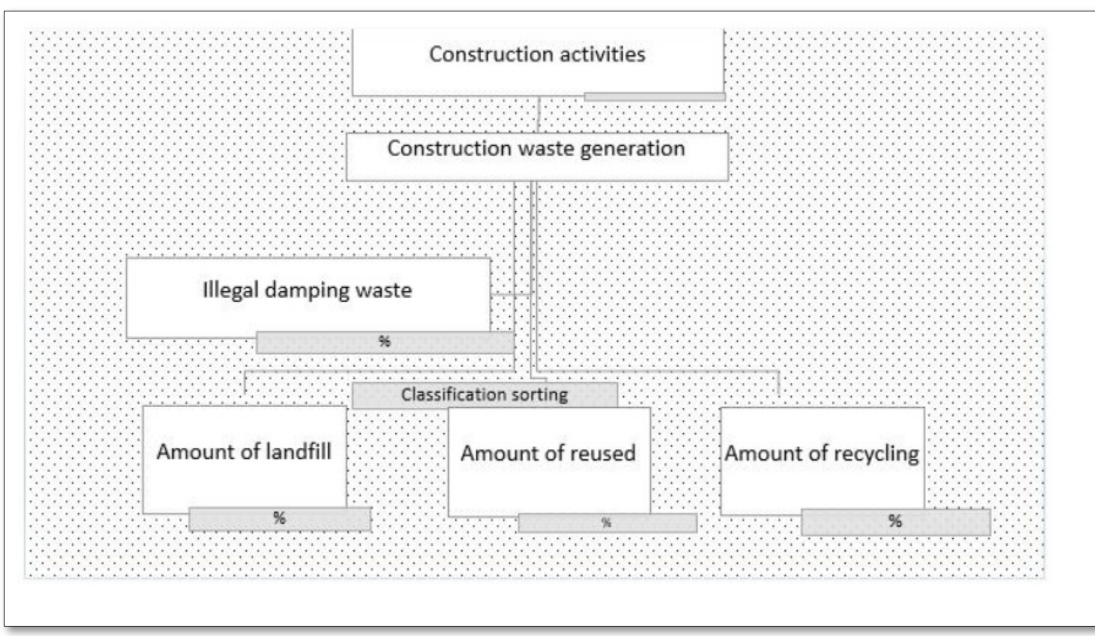


Figure 2-6 Initial flow-chart of the proposed CDW management strategies

According to Bala et al. (2017), waste is generally divided into two categories: (1) un-cleared and non-recycling waste and (2) recycling waste. The equation below expresses that waste generation increases un-cleared non-recycling waste, while collection rate decreases it:

$$Unclearednonrecycling(t) = Unclearednonrecycling(t - dt) + (wastegenerationlevel - Collectionlevel) * dt \quad (2.1)$$

The per capita income population and GDP growth are critical factors in non-recyclable waste generation, expressed as:

$$Wastegeneration(Non - recyclablewaste) = population * wastegeneration/capita * 365/1000$$

$$F_{concrete} = P_{concrete}(1+\Delta \text{ GDP})(1+\Delta \text{ Population}) \quad (2.2)$$

Where:
$F\_concrete$ = future production of concrete waste
$P\_concretet$ = Present production of concrete waste (2.3)

Both generation and collection capacities directly affect the waste collection rate. If the waste generation capacity is higher than the waste collection capacity, the collection rate equals the collection capacity. If not, the collection rate equals the generation capacity. This is expressed in the following formula:

$$Waste\ collection\ rate = IF\left(Generation_{capacity} > Collection_{capacity}\right)THEN\left(Collection_{capacity}\right)ELSE\left(Generation_{capacity}\right) \quad (2.4)$$

Average per capita income, population size, and the recyclable waste factors contribute to the recyclable waste generation rate. The following formula represents this relationship:

$$Recycling\_waste\_generation\,rate = population * per\_Capita\_waste\_Generation * Recyclable\_factor \quad (2.5)$$

Recyclable collection factor, recyclable waste and separation multiplier for public concern most of the contribute to the recyclable collection rate; this is shown as:

$$Recyclable\ collection\ factor = recyclable\ waste * recyclable\ collection\ rate * multiplier\ for\ public\ concern$$

Un-cleared waste is defined as the relative amount of un-cleared recyclable and non-recyclable waste that has not been collected. Of this un-cleared waste, untreated and uncleaned waste creates public annoyance and contributes to GHG emissions. Therefore, abandoned CDW also contributes to climate change and public concern. The impacts of these concerns are limited by the infrastructure for registering concerns (and complaints), expressed in the following equation on public concerns as a "vented reaction":

$$Public_{concern(t)} = public_{concern\,(t-dt)} + (Concer_{rate} - Vented_{reaction}) * dt \quad (2.6)$$

The degree of concern can be quantified as the "concern rate," and this rises with the composite index, having a nonlinear link to the composite index. As a graphical function, this is illustrated as follows:

$$concer\_rate = GRAPH(composie\_index)(0.00,1.00),(25.0,1.11),(50.0,1.25),(75.0,1.35),(100,1.42),(125,1.47)(150,1.50)$$ (Bala et al. 2017) (2.7)

Concerns dissipate or decrease over time; this can be expressed as:

$$Vented\_reaction = \frac{public\_\mathrm{concern}}{concern\_dissipation\_time} \quad (2.8)$$

Public pressure for reducing waste generation is a consequence of public concern. This relationship can be expressed as a multiplier, where the multiplier (public pressure) bears a nonlinear relation with public concern. This is expressed as:

$$public\_(pressure\_multiplier\ ) = GRAPH(public\_concern\ )(1.00, 1.01)\ (2.50, 1.04)\ (4.00.1.08)\ (5.50, 1.25)\ (7.00, 1.25)\ (8.50, 1.35)\ (10.0, 1.50) \quad (2.9)$$

2.4 Analytical hierarchy process application in decision-making

How decisions are made in waste management is fundamental to the success of a project. The techniques of Analytical Hierarchy Process (AHP) are therefore invaluable tools (Liu 2004). AHP was initially developed by Saaty in 1977 as an analytic tool for decision-making. It is able to incorporate multiple criteria for its analyses and translate qualitative values into quantifiable values (Olson, 1996). The principal steps involved in the AHP process are: (1) constructing a hierarchical framework involving the top and bottom levels where the top shows the comprehensive purpose and the bottom shows the alternatives; (2) building a comparison matrix, pair by pair, using a criterion to evaluate the values; and (3) evaluating pair values by calculating the eigenvector of the paired comparison and then evaluating the synthesis of their combined weights (Liu 2004).

MCDM has developed into a mature subdomain in recent years because it has proven itself to be a useful tool for helping choose between quantifiable choice values. This is invaluable for winnowing down a list of options, by pairing one against another and then evaluating them in a step-by-step manner. In this way, AHP is an excellent method for resolving MCDM problems, and it is no surprise that it has seen widespread adoption (Feng, Lu, and Bi 2004)

Therefore, the AHP setup allows the user to quantify engineering data that might not otherwise appear to be available to systematic analysis (Liu 2004). Decision-makers are thereby able to evaluate two simple criteria subjectively and, once these are all weighed, the system weighs the collection of evaluations, showing a result that may not have otherwise been possible due to the great number of individual steps. In this way, what starts out as an overwhelming problem has a simple conclusion because AHP has created a framework for working through the options systematically, creating information that can now go into a model.

People are relatively good at deciding between two simple options but can be quite incapable of making such an evaluation in one step where there are now many options to be weighed (it seems) in a sea of other options. AHP streamlines the process. It is not unlike semifinals and finals elimination between teams in a professional sports league. In short, AHP acts as a funnel and helps people manage what could be intuitive if it was only a simple decision, scaling it up so that a complex problem becomes a series of simple decisions. Therefore, AHP helps create rationality out of what could appear as irrational, reducing uncertainty and guesswork. By systematizing large problems, it can be used to determine probable outcomes and plans efficiently; improve group decisions; and effectively make changes to decision criteria. At the same time, it can help select alternatives, allocate available resources, and provide cost-benefit analyses (Miranda, 2001). AHP has the further advantage of not requiring fine-tuning decision protocols or functions. This is to say, it is an excellent tool for stakeholders who require a means to determine the best outcome when confronted with a great number of discrete but finite choice criteria (Liu 2004).

However, certain shortcomings have been attributed to AHP. One such issue is that while evaluating a problem with AHP, a ranking could be altered or even made to have an opposite outcome by the inclusion of a different choice early in the decision-making chain, even when this new element was not necessarily in and of itself important to the overall choice. In the earlier sports league analogy, imagine a team “A” that was able to exploit a weakness in a particular team “B” that would otherwise not have been meaningful when that team B went up against other teams. When this "lucky" team A eliminates team B it may go on to create a completely different overall outcome, even when team B would have otherwise gone on to victory in the league. Even more critically, Dyer (1990) claimed that following his review of the AHP literature, there is a tendency to assume that the values at higher levels can be weighed independently of those on the lower levels, again pointing to possibly skewed results, depending on how the upper and lower values are laid out.

Dyer (1990) was concerned that the AHP methodology could produce arbitrary results based on such considerations, ones that might well be overlooked. Dyer's conclusion was that AHP must be significantly revised to avoid such a problem, introducing the "revised-AHP." However, advocates of the original AHP have disagreed with Dyer's conclusion. Saaty (1990) claimed that while it is sometimes possible that the choice criteria might be dependent on the placement in the framework, it might also be independent. It can also be affected by the ordering in ways not discussed by Dyer. Saaty (1990) disagreed with Dyer's claim about arbitrary results, stating that "there is good reason for the rank reversal in the relative measurement mode of AHP." Saaty (1990) went on to say that "this is an advantage of relative measurement rather than being flawed as perceived by Professor Dyer" (Liu 2004). On the other hand, Belton (1986) pointed to what he considered the greatest weakness of AHP – the ambiguous evaluation procedure pertaining to the criteria weights and the tendency to implicitly assume that the scores can be rationally reduced.

While AHP has its critics, it continues to be a very practical and widely accepted methodology, and it is held to be the overall most dependable MCDM technique. In the end, it is able to break down a complex problem into a structure that can be framed in a step-by-step manner to address specific objectives and alternatives (Liu 2004). Dahlbo et al. (2015) discuss this problem from "a waste policy perspective and they claim that the results indicate that regional differences in operations and waste composition may support arguments for differing recycling targets in different European regions." The same logic clearly applies to the differences between European or Asian solutions, this study's target area, Libya, and similar countries (Dahlbo et al. 2015).

This thesis focuses on the recommendations of a scenario development study suggested by Knoeri et al. (2011) and Ding et al. (2016). The present study includes two broad divisions. At the project level, the study targets improving waste management awareness and encouraging sorting behavior; at the government level, it includes strengthening supervision by government agencies, refining regulations and controlling illegal dumping. Knoeri et al. (2011) state that the importance of the interaction criteria indicates that there could be important benefits in modelling the interaction of stakeholders in construction. Furthermore, the degree to which a given stakeholder group is heterogeneous needs to be addressed. In this area, there are clear trends in most of the decision parameters. Stakeholders have opinions themselves and therefore they have preferences about decisions. For this reason, it is important to know when and where a given stakeholder is interacting with another stakeholder. One promising area is doing bottom-up simulations, allowing us to capture the complexities of interactions. This facilitates knowing to what extent projected construction material recycling development is sustainable.

2.5 Characterization of demolition waste material properties

2.5.1 Pavement materials used in the building of roads: Libya case study

Several studies have conducted experiments to evaluate road layer material characteristics in Libya (Almadwi and Assaf 2018, 2019, 2021; Amhadi and Assaf 2021; Guha and Assaf 2020; Neves 2019). Some of the above characterizations were used to model and predict road performance over time (Shiboub and Assaf, 2019, 2022). Road pavement building materials are generally categorized as either rigid or flexible. The load-bearing course in rigid pavements is the Portland cement concrete layer, while it is the asphalt wearing course in flexible pavements (Amhadi and Assaf 2021). Increasing axle loads beyond the load-bearing capacity affects the structural integrity of roads, all of which must be accounted for in pavement design (Chen, Saha, and Lytton 2020; Cheng et al. 2020). The four layers generally making up the structure of a road include the wearing, base, and subbase courses, as well as the capping layer resting on the native subgrade.

As a result, the thickness of the road layers, their materials and mechanical properties significantly impact effective load bearing capacity expressed as equivalent single axle loads or ESAL (Han et al. 2020). Of all the layers, the subgrade has the greatest possible dry density or as it is called the Maximum Dry Density (MDD), lowest California-Bearing Ratio (CBR), and highest plasticity index (PI), which results in susceptibility to environmental conditions including high groundwater table (Zhang et al. 2021). To alleviate the recourse to virgin materials, the recourse to CDW above the subgrade will result in a thicker and possibly more rigid pavement to offset environmental issues. (Abukhettala and Fall 2021). Demolition materials from old buildings and pavements can be successfully used as a substitute to virgin materials (Shiboub and Assaf 2019) because they increase the compaction properties and unconfined compressive strength of weak road layers. According to Amhadi and Assaf (2021), in cases of coastal and desert subgrade areas, sand affects the stability of the pavement material mixture when stabilized using fly ash. This type of characterization test validates different conceptual models or hypotheses for developing causal loop diagrams and identifying related factors.

2.5.2 Pavement materials used in the building of roads: Tunisia case study

Assessing the roads in Libya is supported by another case study in Tunisia to validate the simulation model further. Tunisia's cultural, climatic, and geographic conditions are similar to Libya's, but it has stronger infrastructure sector legislation. The present case study was conducted in Tunisia's Rades Port area, which was being developed at the time. The development of the Rades Logistics Zone and the Port of Rades extension will increase vehicular traffic in the Rades Port area of influence. The road sections the MCC and this study examine for the rehabilitation are shown in Figure 2-7 and their dimensions are provided below:

1. The RR33 road section is shown in red and goes from the intersection of the RR33 and the *Pont de Rades – La Goulette* road section to the Rades Port entrance *(730 m long x 15 m wide)*;
2. Road sections in the Rades Port:
    i. Road section 1 is green and goes from the Port entrance to the beginning of road section 2 *(380 m long x 15m wide)*.
    ii. Road section 2 is represented in blue *(1,550 m long x 18 m wide)*.
    iii. Road section 3 is in yellow *(1,500 m long x 14 m wide)*.

iv. Road section 4 is pink and goes from the middle of Road section 3 to the Port entrance *(890 m long x 14m wide)*.

Figure 2-8 Location of developed roads – ArcGIS

The WSP has assessed interior Port roads and the RR33 access road condition, including drainage-related issues, to determine maintenance and technically justified rehabilitation needs.

The pavement surface is in poor condition, resulting from (1) edge cracking from trucks parking along the road and poor drainage; (2) cracking, disintegration and potholes because of asphalt aging, hardening, and a poorly draining base; and (3) longitudinal cracking along the road's middle due to poor construction joints. Observed potholes and disintegrations show the existence of water in the pavement caused by water entering through cracks, and/or the subgrade sucking water from into the structure. The ample presence of water on the carriageway edges, particularly on the RR33, confirms the pavement's poor drainage.

The roads' design and construction records, their current and projected traffic, and the structural capacity of the existing pavement were assessed with the structural analysis software WinJulea. System dynamics can be used in combination with WinJulea to more thoroughly analyze road condition data. The analysis shows the need to reinforce them either through additional material thicknesses or stabilization.

Based on the aforementioned diagnosis of the causes of pavement distress and on the structural analysis conducted on the existing pavements, three different intervention alternatives are justified on technical grounds in the report: (1) a rigid pavement alternative composed a 180-mm high-performance Roller-Compacted Concrete (RCC) layer, covered with 50 mm of high-modulus polymer-modified Asphalt Concrete (AC), resting on a granular base course of 300 mm; (2) a flexible improved pavement alternative composed of a high-modulus polymer-modified AC surface layer, covering a 300 mm reclaimed cement base course; and (3) a flexible pavement alternative composed of a conventional AC surface layer, covering a 300 mm cement reclaimed base course. Because of the important traffic difference in terms of heavy vehicle volume between the RR33 and the other Port Road sections, the above-mentioned intervention alternatives were adapted by varying the thickness of the AC surface layer to conform with structural design requirements. Further information regarding the use of WinJulea in this study see Annexes IV to X.

The economic analysis provides the Economic Rate of Return (ERR) for each road section and pavement solution. The consolidated economic analyses are based on (1) HDM-4 outputs including (1.1) the pavement condition evolution over the 20-year analysis period; (1.2) discounted and undiscounted benefits of vehicle operating costs, time savings, and savings on maintenance; (1.3) the amount of polluting emissions generated by vehicles during the pavement use phase; and separately, (2) an analysis of safety costs and benefits, established based on iRAP and World Bank practices.

As a result of the consolidated economic analysis, the ERR obtained for each candidate road and for each pavement solution are higher than 10%. This excludes additional costs related to truck parking should it need to be borne by the road projects, with no corresponding benefit stream associated to the parking investment.

Port Road 3 has an ERR of 15% with the "Milling + Resurfacing" intervention the WSP proposed because it is the only technically justified solution. There is no need for more capacity and the ERR is high since the IRI is currently elevated. The intervention will substantially reduce the IRI and, therefore, the vehicle operating costs.

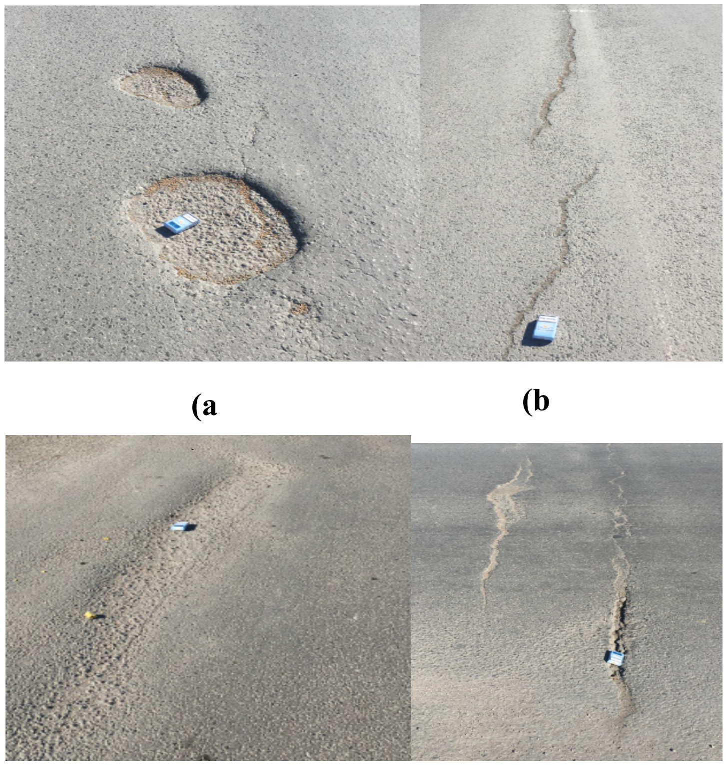
This table provides the total budget, with and without safety, for the recommended solution for every candidate road and its associated ERR, for both traffic growth rates, excluding additional costs (e.g., truck parking) (WSP,2020 a, b). Figure 2-8 shows several examples of pavement in RRP distress, including (a) potholes, (b) wide longitudinal cracks, (c) disintegration and (d) wide transversal cracks.

Table 2.4 Total budget and ERR for the candidate roads

Candidate Road	Safety	Recommended structure	Total Budget (USD)	ERR - Traffic growth rate of 3%	ERR - Traffic growth rate of 5%
RR33 including bridge	Yes	Rigid Pavement (*)	1 677 065 $	22%	34%
	No	Rigid Pavement	1 604 065 $	22%	35%
Road section 1	Yes	Rigid Pavement	521 623 $	14%	16%
	No	Rigid Pavement	483 623 $	15%	17%
Road section 2	Yes	Rigid Pavement	2 279 472 $	9%	20%
	No	Rigid Pavement	2 124 472 $	10%	21%
Road section 3	Yes	Milling + Resurfacing (**)	541 463 $	15%	31%
	No	Milling + Resurfacing	391 463 $	27%	46%
Road section 4	Yes	Rigid Pavement	1 146 182 $	10%	13%
	No	Rigid Pavement	1 057 182 $	10%	14%

TOTAL COST WITH SAFETY	6 165 805 $
TOTAL COST WITHOUT SAFETY	5 660 805 $

Budget for five candidate roads:	**6,200,000 USD**



(a **(b**

(c **(d**

Figure 2-9 Bridge pavement distress

2.6 Pavement design for the most trafficked road section: RR33

Three (3) solutions are recommended for the RR33 road section:

1. **Rigid pavement alternative**: The top layer is composed of 50 mm of high-modulus polymer-modified asphalt concrete (AC), covering 180 mm of high-performance roller-compacted concrete (RCC). The RCC sits on a granular base course of 300 mm (60 MPa), on soil with an assumed subgrade modulus of reaction of 60 MPa/m, calculated based on the Portland Cement Association method as shown in Figure 2-10. AirPave, a mechanistic analysis, was run to confirm the structural capacity of the proposed rigid

pavement alternative (see Figure 2-9 for further detail on the rigid pavement alternative). This pavement alternative will support unlimited repetitions of 18-ton overloaded axle trucks.

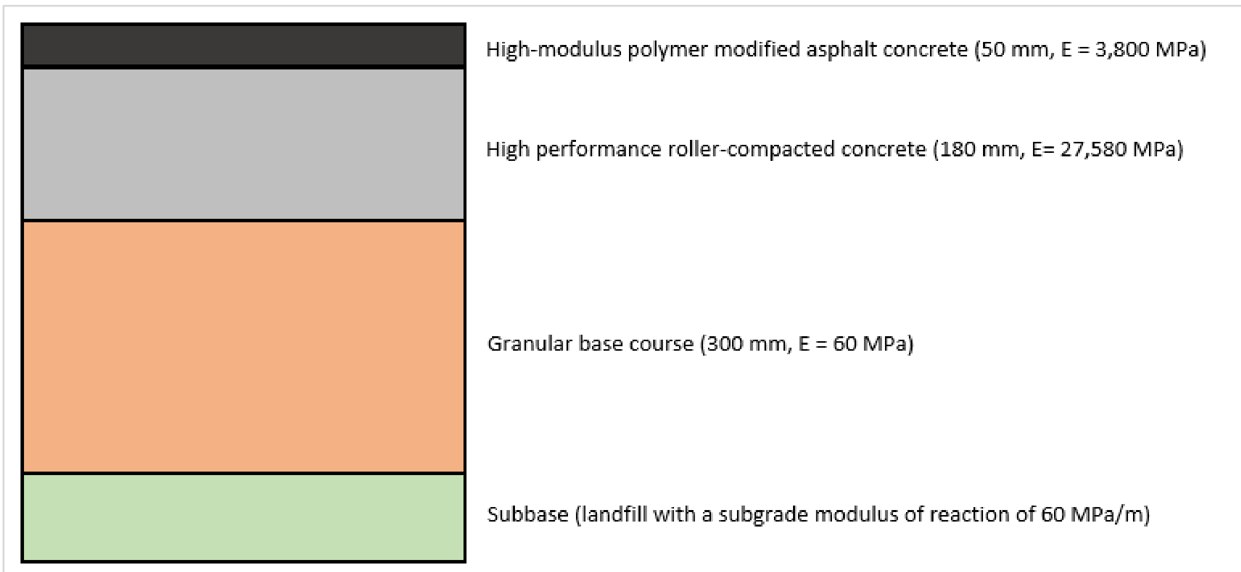


Figure 2-10 Rigid pavement alternative

2. **Flexible pavement alternative A**: The top layer of this structure is a 160 mm high-modulus polymer-modified asphalt concrete with fiber. This pavement alternative deploys a modulus of elasticity of 3,800 MPa covering a 300 mm reclaimed cement base course which itself has a modulus of elasticity of 2,500 MPa. The subbase has a weak capacity with an assumed modulus of elasticity of 50 MPa., equating to a CBR of only 5% (Montanelli et al. 2013).

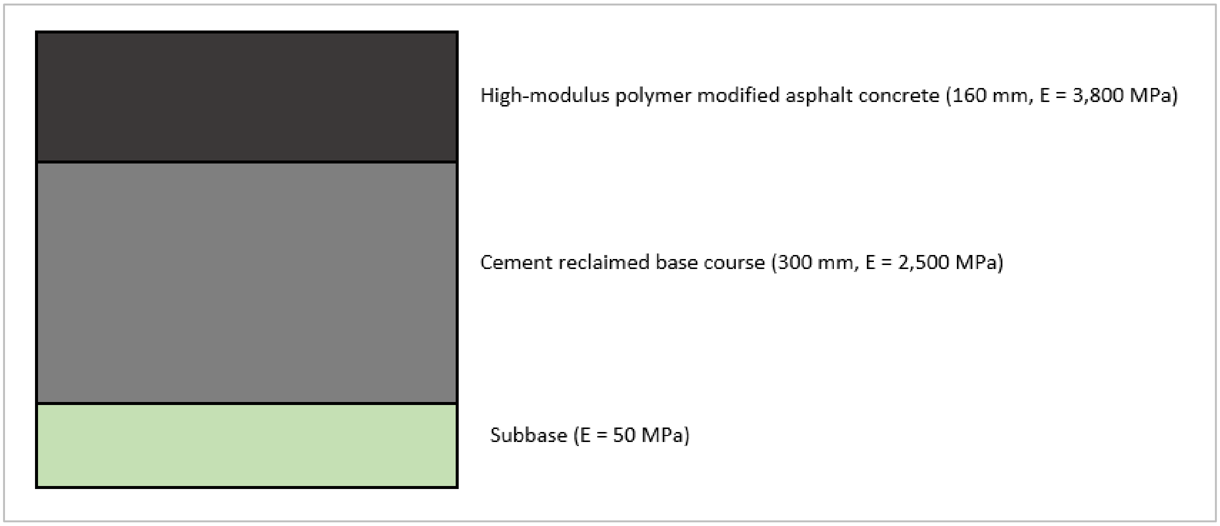


Figure 2-11 Flexible pavement alternative A

Flexible pavement alternative B: The top layer of this structure is a 200 mm conventional asphalt concrete, with a modulus of elasticity of 2,500 MPa. The top layer covers a 300 mm reclaimed cement base course, which has a modulus of elasticity of 2,500 MPa. The subbase has a weak capacity with an assumed modulus of elasticity of 50 MPa. Using AirPave, a mechanistic analysis was run to confirm the structural capacity of the proposed rigid pavement alternative shown in Figure 2-10. This pavement alternative will support unlimited repetitions of 18-ton overloaded axle trucks.

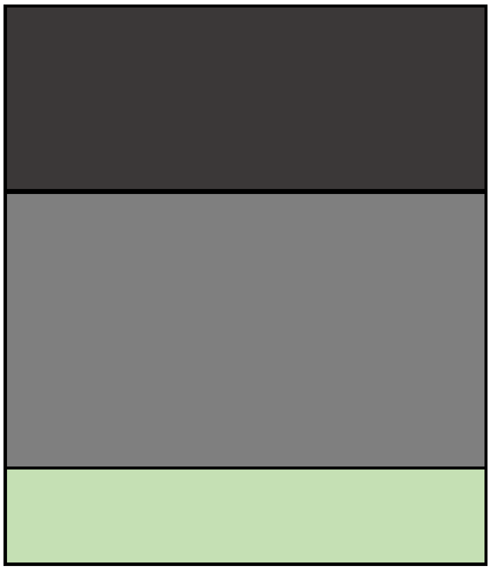


Figure 2-12: Flexible pavement alternative B

2.7 Pavement design for the road sections at the Rades Port

Three solutions are proposed for the Rades Port road sections:

1. **Rigid pavement alternative B:** This rigid pavement alternative is similar to the one proposed for the RR33 road section. The top layer is composed of 50 mm of high-modulus polymer-modified asphalt concrete (AC). Next is a layer of 180 mm of high-performance roller-compacted concrete (RCC), followed by a granular base course of 300 mm (60 MPa) (see Figure 2-11 for the breakdown of flexible pavement alternative B).
2. The granular base course sits on soil with an assumed subgrade modulus of reaction of 60 MPa/m calculated based on the Portland Cement Association method see ANNEX V. Due to the lower current and projected traffic volumes on these roads, the asphalt concrete layer thickness for both flexible pavement alternatives can be significantly

reduced compared to the solutions proposed for the RR33. This change results in significant cost savings.

3. **Flexible pavement alternative C**: The top layer of this structure is a 100-mm high-modulus polymer-modified asphalt concrete with fiber, deploying a modulus of elasticity of 3,800 MPa. The top layer sits on a 300 mm reclaimed cement base course, which has a modulus of elasticity of 2,500 MPa. Finally, the subbase has an assumed modulus of elasticity of 50 MPa and a weak capacity (Montanelli et al. 2013).

4. **Flexible pavement alternative D**: This structure has a 125 mm top layer made of conventional asphalt concrete, with a modulus of elasticity of 2,500 MPa. The top layer covers a 300 mm reclaimed cement base course, which has a modulus of elasticity of 2,500 MPa. The subbase has an assumed modulus of elasticity of 50 MPa and a weak capacity.

WinJulea was used to run two mechanistic analyses to confirm the structural capacity of the proposed flexible pavement alternatives C and D. Results show that, before 20 years, there is no possibility of a rupture by fatigue (see section 2.6.1.1 and ANNEX VII for further detail).

For Road Section 3, with very minimal traffic and enough structural capacity given traffic levels, the only technically justified intervention is “milling + resurfacing.” In particular, it is necessary to mill the existing pavement 35 mm deep and resurface it with 35 mm of polymer asphalt concrete. The ERR obtained is about 15%. No additional capacity is needed, and the ERR is high because the IRI is currently about 3.8 m/km. The intervention will substantially reduce the IRI to 1.2 m/km and with it the vehicle operating costs. The low volume of traffic (only 840 vehicles daily, including 305 trucks) explains the low ERR obtained for this road section.

2.6.1 The effect of the subbase on the subgrade modulus of reaction k

Based on the Portland Cement Association method, the subgrade modulus of reaction of the rigid pavement solution is about 60 MPa/m. The EGIS geotechnical analysis report for the Rades logistics zone reported that the existing soil's structural capacity is very weak (STEG 2014). It has a modulus of reaction of roughly 15 MPa/m, equating to a CBR of below 5%, as shown in the first column of Table 2.5. Reinforcing (1) the subgrade to achieve a minimum CBR of 5% (as shown in the second column of Table 2.5) and (2) the structure with a granular subbase of 300 mm, the modulus of reaction of the subgrade increases from 15 MPa/m to 60 MPa/m.

Table 2.5 Effects of the subbase on the subgrade modulus of reaction k (MPa/m)

		Weak Subgrade 15 MPa/m CBR < 5	Subgrade 25 MPa/m 5 < CBR < 15	Subgrade 60 MPa/m 15 < CBR < 25	Strong Subgrade 75 MPa/m CBR > 25
ABSENCE OF SUBBASE		15 MPa/m	25 MPa/m	60 MPa/m	75 MPa/m
GRANULAR SUBBASE	100 mm	17 MPa/m	30 MPa/m	65 MPa/m	85 MPa/m
	150 mm	20 MPa/m	35 MPa/m	70 MPa/m	90 MPa/m
	225 mm	25 MPa/m	45 MPa/m	75 MPa/m	100 MPa/m
	300 mm	30 MPa/m	**60 MPa/m**	85 MPa/m	115 MPa/m
CEMENT STABILIZED SUBBASE	100 mm	40 MPa/m	60 MPa/m	85 MPa/m	105 MPa/m
	150 mm	60 MPa/m	100 MPa/m	140 MPa/m	175 MPa/m
	225 mm	120 MPa/m	175 MPa/m	225 MPa/m	

2.6.2 Assessment of the structural capacity of the rigid pavement alternative with AirPave

To compare and obtaining more data this thesis uses the American Concrete Pavement Association's (ACPA) AirPave software which is a Windows-based computer program developed by Construction Technology Laboratories, Inc. (CTL). ACPA sponsored the software for the valuation of airport concrete pavements subjected to aircraft traffic. This software is based on the "AIRPORT" computer program that was initially developed by Robert

G. Packard for the Portland Cement Association (PCA). AirPave 2000 assesses the structural capacity of rigid pavements (ACPA 201).

2.6.2.1 AirPave input: Rigid pavement alternative characteristics

High-performance RCC mixtures have properties similar to conventional concrete in terms of modulus of elasticity. The top layer has a modulus of rupture equal to 6,500 kPa and a modulus of elasticity of 27,580 MPa. Finally, the subgrade has a modulus of reaction of about 60 MPa/m. These data are summarized below in Table 2.6:

Table 2.6 Rigid pavement solution characteristics for AirPave simulation

Rigid pavement solution characteristics

Thickness	180 mm
Modulus of Elasticity (E)	27,580 MPa
Modulus of Rupture (MR)	6,500 kPa
Modulus of Subgrade Reaction (k)	60 MPa/m

After that, the structural capacity of the rigid pavement solution is calculated for 18-ton overloaded trucks only.

2.6.2.2 AirPave input: 18-ton overloaded truck input

As Figure 2-13 demonstrates, the following tire configuration accounts for the load distribution and the resultant or overlap of efforts. The WSP assumes a total load of 18 tons per axle because of the absence of overloading regulations. Given the symmetry of the load distribution, only two tires supporting 4.5 tons each are considered. The spacing between two tire centers on the X-axis is about 30.5 cm (see Figure 2-14).

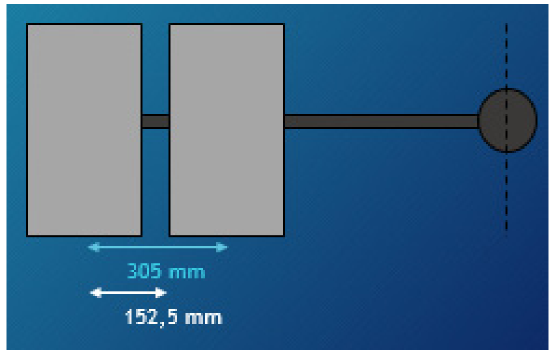


Figure 2-13 Truck description

According to the Tunisian Engineering Company (STUDI) report ("Extension du Quai n°7 du Port de commerce de Rades. Avant Projet Détaillé"), the truck factor is equal to 1.

The standard tire model is 12.00 R 20 (WSP 2020a).

305/70R19.5 LRJ XZA®

PSI		75	80	85	90	95	100	105	110	115	120	MAXIMUM LOAD AND PRESSURE ON SIDEWALL				
kPa		520	550	590	620	660	690	720	760	790	830					
LBS	SINGLE	9530	10030	10530	11030	11510	12000	12470	12950	13420	13880	S	6940	LBS at	120	PSI
	DUAL	17560	18500	19420	20320	21220	22100	22980	23860	24720	25580	D	6395	LBS at	120	PSI
KG	SINGLE	4340	4540	4800	4980	5240	5440	5620	5880	6060	6300	S	3150	KG at	830	kPa
	DUAL	7960	8360	8840	9200	9640	10000	10360	10800	11160	11600	D	2900	KG at	830	kPa

Figure 2-14 Contact pressure for one truck tire (WSP 2020a)

The highest contact pressure (see Figure 2-10) is 830 kPa.

The total weight per tire is equal to 4.5 tons, which equates to 4.5 (tons) * 9.81 (kN/ton) = 44 kN

$$\text{Contact area} = \frac{\text{Total weight}}{\text{Contact pressure}} = \frac{44}{830} = 0.0532\ \text{m}^2 = 532\ \text{cm}^2$$

The contact pressure is equal to 830 kPa, and the contact pressure area is equal to 532 cm^2.

Assessment of the structural capacity of flexible pavement alternative A, with WinJulea

In order to confirm the structural capacity of the flexible pavement alternative A, a thorough mechanistic analysis is presented below. For more information see the ANNEX V1.

2.6.2.3 Pavement characteristics

The top layer of the structure is a 160-mm high-modulus polymer-modified asphalt concrete (AC) with fiber, with a modulus of elasticity of 3,800 MPa. The asphalt concrete layer covers a 300-mm reclaimed cement base course, which has a modulus of elasticity of 2,500 MPa. The subbase has a weak capacity with an assumed modulus of elasticity of 50 MPa (see section 2.6.1.1 and ANNEX VII for more details).

2.6.2.4 Load characteristics

The total weight per ESAL, corresponding to the reference axle in the EGIS report, is 13 tons. Therefore, the total weight per tire is equal to 3.25 tons, and the standard tire model is 12.00 R 20. The highest contact pressure is 830 kPa and the contact area is 384.10 cm^2 [For more information see section 2.6.1.2].

Modes of failure

The pavement's structural design must verify the following failure modes:

1. Failure in compression at the top of the asphalt concrete.
2. Failure in tension at the bottom of the asphalt concrete.
3. Failure in compression at the top of the base course.
4. Failure in tension at the bottom of the base course.
5. Failure in compression at the top of the subbase.

The following mechanistic analysis demonstrates that there is no risk of a rupture by fatigue for at least 20 years. See section 2.6.1.5 and Annex VII for more information.

CHAPITRE 3

A SYSTEM DYNAMIC MODEL FOR SUSTAINABLE CONSTRUCTION AND DEMOLITION WASTE RECYCLING IN LIBYA

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ABSTRACT

In Libya, Construction and Demolition Waste materials (CDW) are currently thrown in landfills or illegally dumped. In regions where the CDW is not landfilled, insufficient CDW management fails to take advantage of the full value of the materials that could be repurposed for road construction. This research aims to develop a sustainable CDW management model appropriate to Libya and similar countries. Over 97% of construction in Libya uses cement; therefore, this study focuses on cement production and consumption and creates a simulation to model the parts of the construction industry. This study uses System Dynamics (SD), which is a tool used by stakeholders in policy planning to make better decisions about how to manage CDW. This study models and predicts CDW from 2008 until 2030, taking material cost, availability, recyclability and environmental, economic, and social impacts into account. The model conforms to historical data from 2008 to 2016 and then becomes a predictive model until 2030; the years following 2011 are particularly critical due to the amount of destruction and the resulting rebuilding. The model shows that having a higher collection budget does not result in better environmental outcomes unless there is money allocated for CDW recycling. The study quantifies the amount of material in Libya generated from demolition that is not reused; this data becomes a means of analyzing the value of the waste. The model output provides important data (e.g., cement consumption, GDP) for future resource management.

Keywords: Recycling, CDW, System Dynamics Modelling, Cement Production, Road-Construction-Libya

3.1 Introduction

Both developed and developing countries face the challenge of adequately managing natural resources in a way that improves the environmental, social, and economic development, or sustainable development (SusD) relating to Construction and Demolition Waste Materials (CDW). In this study, the focus is on a developing country where such CDW management has reached a crisis level, namely Libya, where the data were collected. CDW in Libya is at a crisis level because Libya suffers from a lack of suitable materials for public works projects and road construction, for example, gravel and angular sand (Almadwi and Assaf, 2018). Transportation and depletion of these materials have enormous consequences on SusD. Also, there is a large amount of demolition material resulting from the current civil war in Libya that leads to waste. If the appropriate decision is not taken to deal with these materials, it will increase the current crisis. Instead of using recycled materials that could come from construction and demolition as well as from civil war, current projects are using virgin raw materials. This can lead to two consequences. The first is the clogging of disposal sites where the waste represents a liability for the environment. The second is the loss of the potential value of the waste material by not reusing it. To date, no one has looked at reusing the demolition material from the civil war as well as other sources for construction projects.

Issues about the environment, including landfill availability and natural habitat destruction due to factors such as quarry excavation and landfills, have become important problems in need of policy solutions at the national level (Chakra & Machaka, 2015). The objective is to establish and identify the essential elements of the SD model for CDW.

3.2 General issues

Sustainability is one of the most important criteria when developing a framework for recycling CDW. CDW is the result of "activities such as the construction of buildings and civil infrastructure, total or partial demolition of buildings and civil infrastructure, road construction and maintenance" (Environment Commission, 2014). Infrastructure in society is an ongoing and growing societal need at the core of the well-being of the community but also one that generates a lot of waste. In essence and for practical purposes, most CDW consists of stone, brick, concrete, mortar, and asphalt; particularly in more recent construction, there are also materials such as glass, wood, metal, plastic, and contaminants such as silt, silicates, sulfate, chlorides, and organic materials (Di Maria, Bianconi, Micale, Baglioni, & Marionni, 2016). What can, for instance, be easily controlled is what selection of materials are approved as being "sustainable." According to Waris, Shahir Liew, Khamidi, & Idrus, (2014) this selection process may be the easiest means for a project to ensure sustainability in the implementation of construction projects.

Marzouk and Azab (2014) claim that there is a still greater problem in developing countries such as Egypt. Here there are very large amounts of waste that need to be processed. At the moment, there are no systematic means of recycling it, and most waste is simply disposed of, either legally or illegally, and not processed or recycled. Such a situation will present serious economic concerns in the future. Currently, the money allocated to the problem is used to put the waste in a landfill and to minimize the problems associated with landfilling. All of this contributes to a growing sustainability problem, the details of which include: (1) the depletion of raw material, (2) shrinking space available for landfills, (3) environmental damage, (4) increased energy consumption for new material manufacturing, and (5) contamination from landfill leakage into the soil and off-gassing into the atmosphere.

Until the 1930s, in developed countries, the mechanism of material selection and decision-making and the objectives of construction were always to minimize the original cost of this construction. Since that period, there has been a growing awareness of the disadvantages of this approach because the objective of having a low cost for the initial project might conflict with the objective of having low ongoing operation and rehabilitation costs (Akadiri, 2011). For example, a building might be cheap to build but expensive to operate (e.g., to heat or cool). For this reason, there has been a shift in emphasis at the regulatory level in many countries; there is now a greater focus on the life-cycle costs of the entire project. Life-cycle Cost

Analysis (LCCA) is, therefore, an important tool in the economics of construction projects, especially in the public sector of many countries.

Another equally important economic evaluation technique is Life-cycle Costing (LCC), which quantifies all costs such as increased safety, reduced emissions, and other usually non-tangible costs and benefits. LCC can thus be used for decision-making and is especially useful for choosing between different construction material options (Arpke & Strong, 2006). While LCCA is useful, it has to be multidimensional and to account for environmental and social effects due to the many factors that must be taken into consideration in the interface of human activities and the environment (Akadiri, 2011). It may also be difficult to balance out the concerns of all stakeholders. These sustainability issues must, therefore, include minimizing environmental, economic and social concerns. In order to address the concerns of all stakeholders, there are a number of factors that must be kept under control.

CDW is not easy to calculate and is easy to underestimate. For example, the 2012 CDW estimates for Europe (EU-28) were approximately 820 million tons per year. This represented about one-third of the total waste generated. In the US, the estimate was about 480 million tons. In India, with a population approximately three times the size of the US, it was approximately 530 million tons, according to 2013 estimates. The European Directive on waste (2008/98/EC, otherwise known as the "Waste Framework Directive") has set targets of at least 70% recycling and reuse of CDW by 2020. In response to this, a great effort has been deployed towards CDW reduction, reuse, recycling, and management. This said, there is a general consensus that the main problems with regard to CDW reduction are material quality and economic viability (Di Maria et al., 2016).

For instance, Finland currently falls short of the average European recycling target of 47%; to create incentives for projects to recycle CDW, Finland, as of 2016, has restricted the disposal of waste in landfills. This new regulation may create more demand for other ways of using waste plastics and wood in particular (Dahlbo, Bachér, Lähtinen, 2015).

Poon (2007) and Azad., Zarmina, (2015), discuss examples from areas in Hong Kong as well as in mainland China and Pakistan where they must account for the dramatic limitations on land availability. There, CDW has obstacles to aggregate reuse that are similar to those existing in other areas; these problems include: (1) the low cost of landfill disposal, (2) the absence of taxes on cheap virgin raw aggregate, (3) lack of progressive regulations on contractor requirements, 4) lack of education within the construction sector about the application of recycled aggregate.

Duran et al. (2006) outline certain preconditions necessary before this situation changes. One precondition is that the cost of bringing CDW to a recycling center should be lower than bringing the same CDW to a landfill. A second factor is that the costs of similar recycled materials become cheaper than raw virgin materials. For example, in roadwork, the cost of recycled aggregates should be cheaper than the cost of primary aggregates. These cost factors rely on the properties of demolished materials and how they have been mechanically treated (Boateng 2017; Huang et al. 2002; Tam and Tam 2006). For this purpose, studies confirm that such recycling is a reasonable substitute for natural raw virgin aggregates. These factors lower the market demand for recycled materials and limit the interest in businesses that might focus on such materials. Renovation, construction, and demolition all produce CDW in varying amounts, regardless of the size of the project. CDW composition, quality and amount are not standard from site to site, region to region or even country to country (Dahlbo et al. 2015). For example, a Finnish study showed that, in 2007, there were about two million tons of CDW (non-hazardous) generated in the following stages: 16% construction; 57% demolition; 27% renovation (Dahlbo et al., 2015).

In recent years, there has been a large and noticeable expansion in building construction in Libya (Ngab 2007). In addition, there are a great number of maintenance projects. So that they can be recycled in the future, the design and the selection of materials for any new construction both need to be of high quality. This expansion makes some stakeholders and authorities think about the objectives of the construction industry in sustainable ways. In Libya, the last decade has seen construction practices without suitable planning or promotion, and these projects are not sustainable construction environments (OECD 2016). In order to create such environments, there must be initiatives to encourage or even regulate sustainable development (Ali and Ezeah 2017)

3.2.1 The quality of Libya's infrastructure

Libya has geographic advantages with its position on the Mediterranean Sea and the need for Egypt and Tunisia to connect by land. Private sector development relies on everything from roads, ports, airports to telecommunications and the electrical grid. Such an infrastructure must be reliable for the regular delivery of goods and services to get to market. Without these, the competitiveness of the country's economy will suffer due to heightened transaction and trade costs. Before the 2011 revolution, Libya already had an infrastructure that had been deteriorating for years.

Table 3.1 Deterioration of the road and electrical infrastructure (2016, p.49)

Indexes for Organizational Structures and Facilities	GCI 2014-15		GCI 2013-14		GCI 2010-11	
	Value	Rank/144	Value	Rank/144	Value	Rank/144
Total of the infrastructure quality (transportation)	1.9	144	2.3	144	3.2	115
Transport Infrastructure						
Road Quality	2.1	142	2.5	134	3.1	97
Port infrastructure Quality (Out of 7)	2.6	131	3.0	124	3.2	116
Air transport infrastructure (Out of 7)	2.4	139	2.9	136	2.9	133

By 2010, decades of isolation and neglect placed the country in 115th place on a list of 139 countries on the Global Competitiveness Index (GCI) for its overall quality of infrastructure. The 2014 ranking put Libya in the last place, 144 out of 144 as per Table 3.1. By this time, the road infrastructure had further deteriorated due to the ongoing conflict. Production levels and associated revenues had gone down. As of 2012, Libyan government officials projected that the US $40 billion should be invested in transport infrastructure alone (OECD 2016).

Additionally, where the level of sensitivity to reuse and knowledge about it are high, there are still other obstacles to sustainable development. To take national strategies for sustainability and implement them at the local, project level is not an easy task, as pointed out by (Ding et al. 2016).

In the future, the makeup of CDW may change because aging structures will either need renovation or come to the end of their useful lives (Boateng 2017). How these new factors will affect CDW composition is not known. Particular questions pertain to how these factors will affect targets or if substantial reforms to the system must be undertaken (Shiboub and Assaf 2019).

Reasons against sustainable development could be that it will continue to be cheaper to find sources of raw materials and continue to be cheaper to dispose of waste in landfills. Some believe it is cheaper now and will always be cheaper to find new resources and to put waste in the landfill. Finally, there is the question of risk; many believe it is not worth being innovative when doing so risks failure and disgrace. This is common in many areas and is referred to as an institutional barrier against change.

3.3 Cement consumption values in Libya

This research is distinguished by how it introduces cement production and consumption modelling to construction. As discussed by Ali, Ezeah, & Khatib, (2016), cement is essential to concrete production, and over 97% of construction in Libya uses cement. This is why from the beginning a statistical analysis of cement production must include estimates of the amount of concrete in CDW in present-day Libya. From this, the amount of cement that is imported into the country or produced domestically can be calculated; modelling the CDW also helps calculate the amount of cement used in construction in Libya. Once the model has been established, other construction materials can also be analyzed. These analyses are only possible due to the good quality of Libyan cement use records; because of Libya's unstable political situation, these analyses are the best means to evaluate CDW in Libya. Fieldwork is not currently possible. Furthermore, construction projects often suffer from a lack of quality data of the quantity and kind needed for research. As discussed by Shiboub and Assaf (2018), an alternate means of qualifying this data is to compare them, using a per capita analysis, to countries with equivalent economic and social characteristics; in other words, countries that draw their main economic power from oil exports and those that share similar cultural factors.

Previously, Libya was viewed as having the highest cement consumption in the world per capita, with an average of approximately six million tons per year (Ali et al., 2016). Starting in 1992 and up until 2006, cement consumption rose markedly, going from approximately four million tons a year to approximately seven million tons a year; this rise was due to the great quantity of government development projects.

Some projects had been started by the government to augment cement production in Libya, with a production target of approximately 13.5 million tons by 2010; at that time, Libya was producing around ten million tons each year (Ali et al., 2016). Because Libya needs more cement than it produces, it has imported cement from its neighbours, including Turkey, Tunisia, and Egypt (Ali et al., 2016). Before 2011, there were plans to increase the level of cement production to about 15 million tons, and the Libyan government had gone so far as to issue permits to a number of foreign corporations to compensate for the shortfalls in production (Shiboub & Assaf, 2018).

The priority of this research is to develop a sustainable CDW management model appropriate to the economic, physical and social environment of Libya and similar countries. In order to reduce pressures on landfills and to decrease demand for waste removal, recycling the CDW materials is the best and most sustainable way forward.

3.4 Methodology

1. VENSIM PLE software is used in this study to create a system dynamics (SD) model. The advantage of the program is that it has a graphical user interface (GUI) which helps the user to design and to test the SD model.
2. This SD model is targeted at reproducing the Reference Behavior Patterns (RBP) of the sector of road construction as it relates to buildings to be reused, recovered, and recycled into road construction base and subbase materials. After establishing good definitions for these, considerations of how community behavior and policies affect the recycling objectives must be determined in order to shift the community to eliminating landfill waste.
3. The SD model aims at improving understanding of current community behavior and will help develop strategies to change this behavior.
4. The data, once aggregated, will ensure the usability of the model. All materials that can be recycled will be counted in a group. GDP average growth rates, as well as the portion of GDP that goes to cement production, will be used to determine user base totals; for the purposes of modelling, this base is considered to be as active as possible, within the scope of the available facilities. To the extent that this aggregation affects model results, it is presumed to be minimal; considering the scope of the project, the trade-off is likely reasonable.

3.4.1 Various Scenarios for Choosing Parameters

According to Shiboub & Assaf (2018), building a model necessarily starts with GDP, growth rate of average GDP, and net change in average GDP. In this study, additional significant factors were added, e.g. population and population growth because these are the most reliable indicators for economic growth and the construction that accompanies it. GDP average growth rates and the fraction of GDP that goes to cement production are essential behavioral factors in the generation of waste, as illustrated in Figure 3-1 and shown in Equation 3.1.

$$\boldsymbol{F_{concret} = P_{concret} * (1 + \Delta GDP) * (1 + \Delta Population)} \quad (3.1)$$

Where:

$F_{concret}$ = Future production of concrete waste;

$P_{concret}$ = Present production of concrete waste

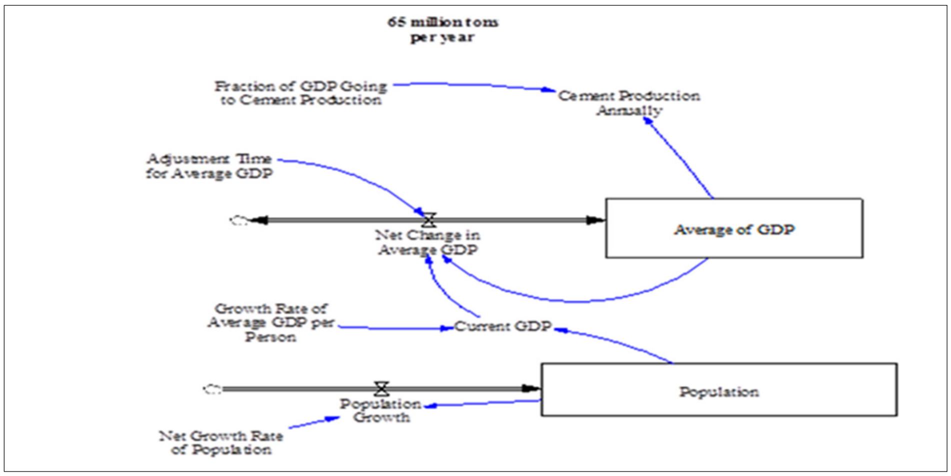

Figure 3-1 The model benchmark for CDW
management and the flows and stocks with model factors

The time period for the simulation is from 2008 until 2030. This allows enough range for annual historical data to be used; for the years from 2008 until 2016, the simulation should match the recorded historical data, creating a baseline. The most important years in Libya are the years following the 2011 revolution because during this period many buildings were destroyed. Following this period, there were a lot of new growth projects. The last year that will be used for historical input data is 2016. From 2017 until the end of the simulation in 2030, the output data will be considered as a future projection; see Figures 3-3 to 3-4.

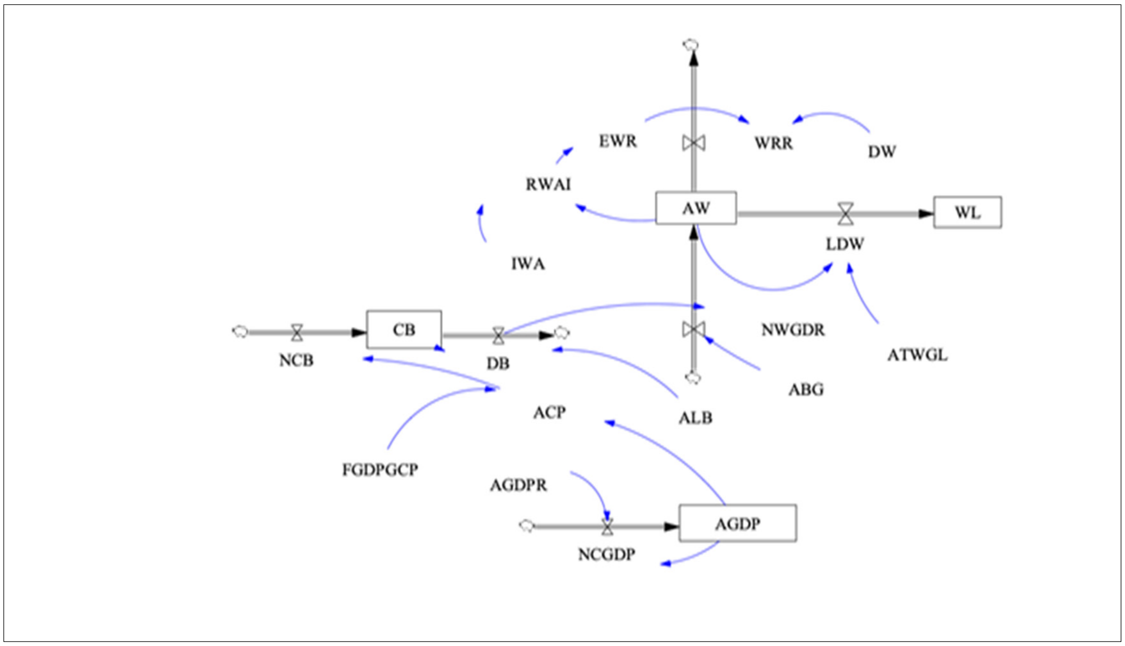

Figure 3-2 The model benchmark for CDW management and the flows and stocks with model factors

In the model, the following internally determined factors are important: The *Available Waste*, *GDP*, *Annual Cement Production*, *Landfill-Designated Waste*, *Waste in Landfills*, *Cement in Buildings, Demolition of Buildings*, *New Construction of Buildings*, *Population and Population Growth*, and *Waste to Road Recycling*, etc.; see Figures 3.1 and 3.2. Once these are known, a sustainable CDW recycling program can be developed. Both Available Waste (AW) and Waste in landfills (LDW) directly affect the WL. In the case where AW capacity is more than the LDW capacity, the AW rate equals the WL capacity; if not, it equals AW capacity. This is expressed in the Following formula:

$$AW = if\,(WL > LDW)\; then \rightarrow\; AW\; \rightarrow else \rightarrow\; (WL) \tag{3.2}$$

Where: AW: Available waste; WL: Waste in landfills; LDW: Landfill-designated waste.

3.5 Results and Discussion

The model benchmarks that have been created for CDW management are as follows. Annual Cement Production has similar results to Landfill-Designated Waste. This is also true of the flows and stocks that use factors from the model. Annual Cement Production has been regularly increasing over time, and it is an important indicator. These factors help stakeholders develop appropriate strategic plans for CDW recycling. Figure 3-3 displays the annual cement production, interaction and simulation behaviors over time.

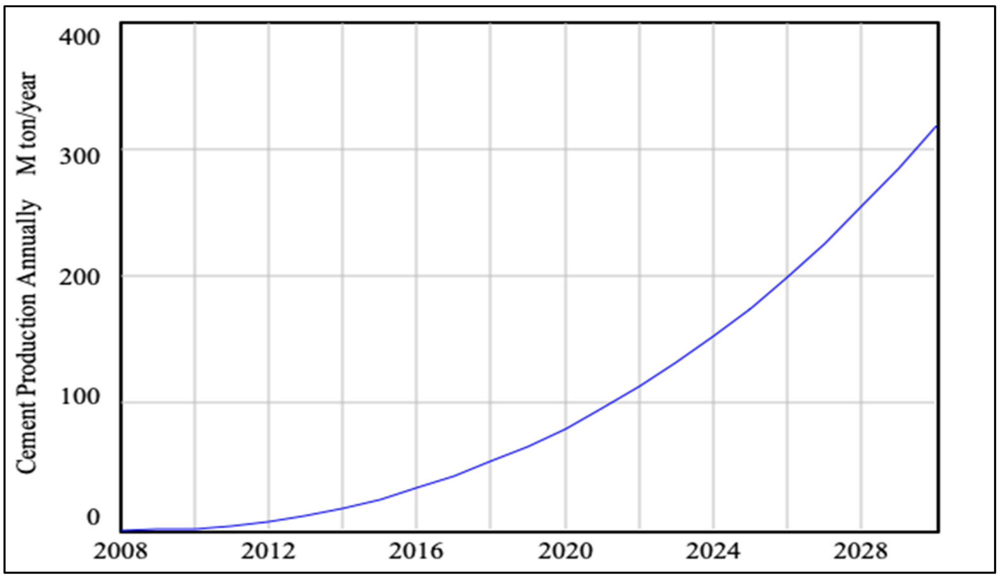

Figure 3-3 The Results, Annual Cement Production, interaction and simulation behaviors over time

As Figure 3-4 shows, in the middle of the simulation shows, 2020 for example, the annual production of cement will reach around 90 million tons; by the end of the simulation in 2030, the annual production of cement in Libya is approximately 300 million tons due to the great amount of reconstruction and the new planning projects. The model takes into considering the projections for GDP growth, which is tied to the growth of the population; the population estimates for 2030 in the model are approximately 10 million as is illustrated in Figure 3.4.

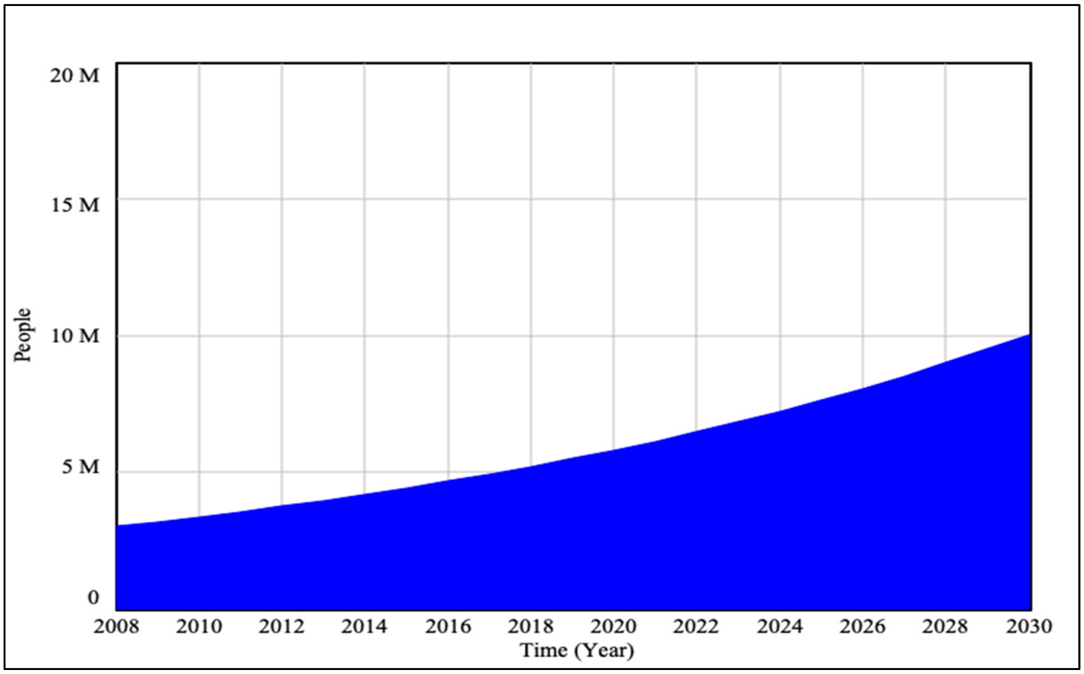

Figure 3-4 The Results, Current Population and
Estimated Population in 2030

Net Change in Average GDP, Annual cement production, Cement in Building, New Construction of Building and Fraction of GDP Going to Cement Production all contribute to the Waste-to-Roads Recycling rate.

The results in Figure 3- 5 illustrate how the behavior and the relationships between the factors in the model increase steadily over time; these factors are *Available Waste, Average Building Generation,* and *Waste in Landfill*. When the *New Construction of Buildings* variable is at a high rate, the *Waste in Landfills* rate increases, in this case, the overall *Available Waste* rate can appear to grow very quickly. Problems can arise when the CDW increases but the waste is not treated, as discussed. In these cases, the CDW is likely to be put in landfills instead of being reused or recovered. An attempted solution is to substitute natural aggregate, for example, with recycled aggregate from municipal waste; this substitution results in concrete that has no important difference in its compressive strength while resulting in a significant environmental benefit (Chakra & Machaka, 2015).

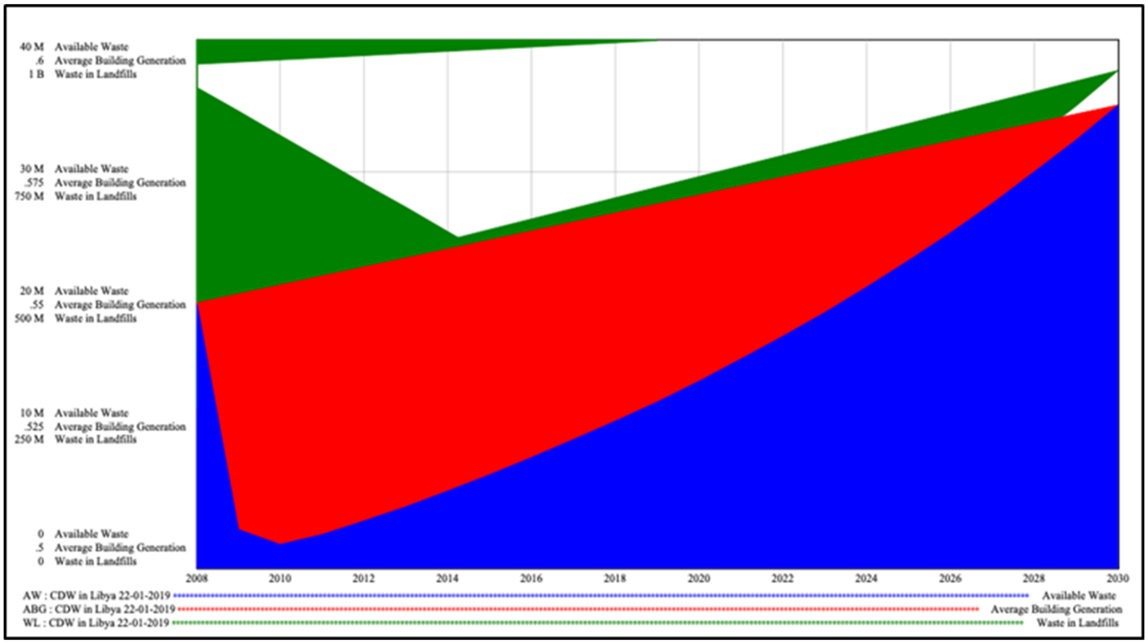

Figure 3-5 The results of the Available Waste,
Average Building Generation, and Waste in Landfills

As shown in Figure 3.6, such programs usually grow exponentially in the beginning and then their growth levels off once some saturation is experienced in the system, in what is called a sigmoid or S-shaped growth curve; this can be compared with J-shaped growth, where the growth is very fast and then stops. However, they are typified, such a growth pattern needs to be avoided. Which is to say, often there is a pattern whereby the early adopters are receptive to the recycling program, and so the adoption of the recycling seems to grow in relation to the waste generation. Nonetheless, over time the recycling behavior tends to level off and not keep pace with the waste generation.

Figure 3-6 Relationship of the rate to Waste to Roads Recycling rate.

3.5.1 Budget allocation and trucks required

The Collection Cost comes to $250 per building, a cost also designed to influence the benchmarks in the model. Cost of CDW is set at $300, which is the per-building cost at which Effect of the Waste elements is given a high motivation to become the High Rate Waste to Road Recycling variable. Figure 6 indicates the overall funding needed for CDW collection, landfilling and treatment over 25 years

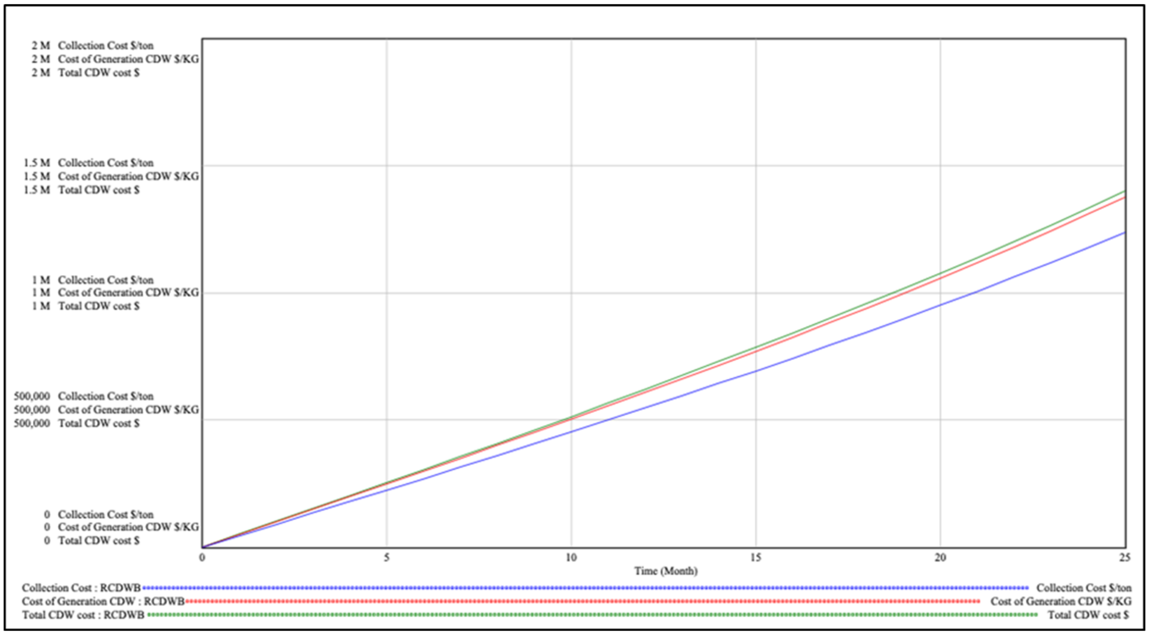

Figure 3-7 Simulated total CDW cost needed for important elements

The results in Figure 3.7 with the following elements illustrated: The *Collection CDW Cost dollar per ton,* Cost of CDW *Generation,* and Total *Cost* (as a percentage of total) for 25 years of collections. The *CDW Collection Cost* in the total simulation increases over time because the overall number of CDW goes up; see Figure 3.8. Therefore, the required cost for CDW goes up to $500 per ton from the initial years.

According to these results, CDW processing *Total costs* go up for a period of 15 years and then the costs reach a relatively stable value of 1.5 million dollars due to how the use capacities of the processing centres are implemented. Note that in the same simulated period other costs also go up. These higher costs
are because both the CDW processing capacity and the landfilling capacity approach their optimal maximum levels.

According to calculations, the total costs go higher, while total costs for managing CDW also go up. As such, a higher financial investment is required to manage both the collection and the processing of CDW. Figure 3.8 illustrates the optimal quantity of trucks.

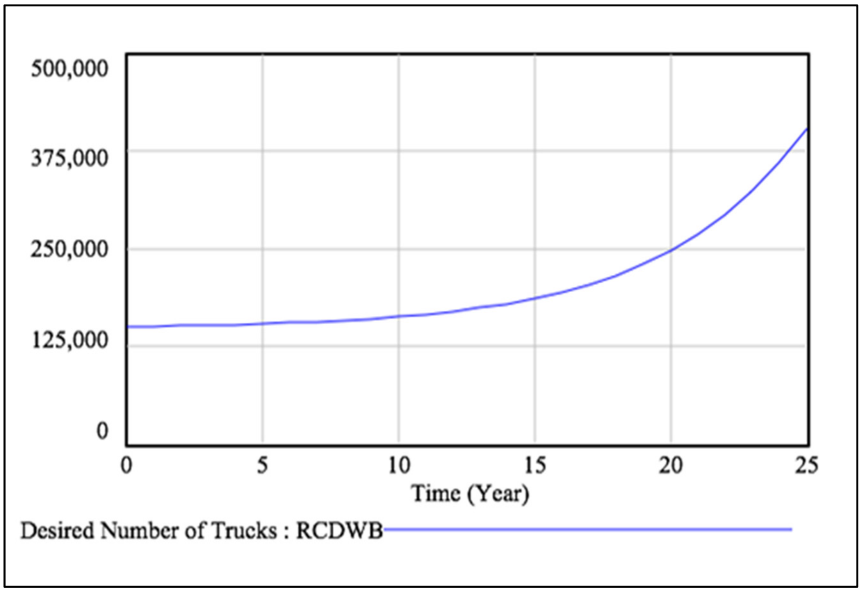

Figure 3-8 The optimal quantity of trucks
per building per year

The total budget surpluses and deficits, the financial surpluses and deficits needed for CDW collection are simulated as a function of the percentage of available funds over 25 years. In the simulation, the optimal quantity of truck goes from 135 in the first ten years to 400 in the last year, while, over the same period, the recorded quantity of trucks goes from 125,000 in the first year to 450,000 by last year of the projection. This is to say that there is a notable difference between the optimal and actual quantity of trucks.

Due to this difference, the quality of the CDW collection is getting worse, not better. Also, moving the CDW to the landfill is not well executed. CDW has been reported falling off of trucks during collection. CDW normally increases with the population because more buildings are constructed to house the greater population; as such, the optimal quantity of trucks increases. Therefore, there is a serious shortfall when it comes to a budget for CDW collection, especially with regard to trucks.

3.5.2 Verification and validation

Verification and validation become more straightforward as the model is developed due to how these constituents interact. They can be reduced to three categories, each including features of the validation methods that were used. In this research, validation depends on the three following elements: (1) ensuring that the model works according to plan and that the input data are correct, and (2) verifying results with those from successful previous research (e.g., Bala, Arshad, & Noh, 2017; Mashayekhi, 1993); (3) modelling a particular building, the details of which are below. The present research has completed the first two of these verification steps.

3.6 Conclusion

To address the problem of CDW materials being landfilled or, worse, illegally dumped in the outskirts of residential areas, it is critical that we understand the scope of CDW generation so that policy can be developed to address the problem. This paper has shown the preliminary results of an SD simulation model that incorporates historical CDW data to project future CDW generation over time. This model is tracked to such data as GDP and population growth as well as cement production and consumption. In the years covered, from 2008 until 2030, the model results that the CDW in Libya will grow from 500 million tons in 2008 to ~1billion tons in 2030 as is shown in Figure 5. This indicator includes a large amount of demolition material resulting from the current civil war in Libya that leads to the large of waste. Also because of the people who live outside the country and are expected to come back, as well as the people who are expected to immigrate to Libya in the future, such as workers for new companies, etc. Policy initiatives are needed to ensure that this growth in CDW is directed to the right pathways, i.e., recycling and reuse so that the material could be repurposed to become base and subbase layers in roadway construction. Were it to be illegally dumped, it would result in the twofold problem described above, namely that there would be an unsustainable strain on virgin raw materials and at the same time a growing crisis in disposal with the known environmental, social, and economic impacts. The situation in Libya is stark because of the lack of governmental oversight at the local level and the absence of regulation at the national level. At the same time, the economy and population are both growing, despite the ongoing conflict, which itself is responsible for a great deal of CDW. This situation is not unique to Libya but is shared with countries such as Syria and Iraq and, not long ago, Lebanon. This is to say that the development of this simulation model as a tool for sustainable environmental, social and economic policy and eventually recycling centre development may, unfortunately, have wide use in countries that have experienced comparable social and historical events as Libya.

CHAPITRE 4

DESIGNING A SYSTEM DYNAMICS MODEL THAT PROMOTES A CIRCULAR ECONOMY OF ROAD DEMOLITION WASTE

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ABSTRACT

Purpose – This paper uses system dynamics modeling to propose a novel circular economy of road demolition waste (RDW) management. Extant literature shows that government regulations, subsidies, fines, and dumping fees fail to change RDW management stakeholder behavior due to political, cultural, social, and economic barriers. Therefore, this model addresses these obstacles by establishing a novel RDW management stakeholder incentive strategy called the virgin-for-used-material exchange (V4UX) program.

Design/methodology –The present study triangulates data and research methods (e.g., an open-ended system dynamics model, interviews, and a case study) to design and validate the V4UX (i.e., technical systems analyses, model testing and validation, and policy analyses).

Findings – Results support the V4UX, which lowers a road's environmental footprint, improves its performance and lifespan, fosters stakeholder participation, and increases financial savings.

Research limitations –The present study has various limitations to the proposed model's impacts and scope. Two examples are a lack of funds and stakeholder ignorance regarding SD and recycled RDW. Future researchers should identify and analyze SD implementation issues among nonacademic stakeholders.

Practical implications – The V4UX could help countries facing similar RDW management challenges, especially developing countries.

Originality/value – This work addresses the urgent need for a circular economy of RDW management systems via the V4UX. It also cultivates stakeholder participation and identifies several critical elements for the circular economy by creating a closed-loop diagram.

Keywords: System Dynamic Modeling; Road Demolition Waste Management; Developing Countries; Road Rehabilitation and Construction; Circular Economies; Recycling.

4.1 Introduction

One of the biggest challenges of road rehabilitation projects in many developing countries is getting local stakeholders to accept that recycling road demolition waste (RDW) improves road performance (Shooshtarian et al. 2020; Wahlström et al. 2020). Over the last few decades, idle RDW has continued to accumulate worldwide.

Although the International Finance Corporation's (IFC) performance standards require prioritizing sustainable engineering decisions, stakeholders are reluctant to use them. This reluctance is partly due to misperceptions that demolition materials are non-recyclable, and their use in construction is "cheap" and unreliable, leading to poor road performance (IFC 2013). Other obstacles include (1) the absence of waste disposal education, regulations, and enforcement; (2) the wide availability of illegal dumping sites (Pariatamby, Bhatti, and Hamid 2019); and (3) cheap virgin materials (VM), such as limestone aggregate (Oliveira Neto and Correia 2019).

Regulations, fines, and high dumping charges are traditional approaches to changing stakeholder resistance to using recycled RDW (Hu, van der Voet, and Huppes 2010; Jia et al. 2017, 2018). However, stakeholders have a well-documented tendency to ignore fines or bypass the system (Hongping 2011; Pedde 2017; Yuan and Wang 2014). In developing countries, high fines are counterproductive as they increase corruption in various ways. For instance, they can (1) spend resources on evading liability by falsifying monitoring reports; (2)

cover up pollution; (3) challenge legislation, jurisdictions, and enforcement decisions in court; and (4) bribe officials (OECD, 2004). Additionally, the OECD (2016) reported that cash incentives given to contractors increases corruption (e.g., cash can be used for bribes and to buy VM) and are thus, major constraints to sustainable development (OECD 2016; Puri and Nichol 2015; World Bank Group 2020). However, Brooks (2016) showed that even when socially tolerated, corruption diminishes when there are fewer opportunities to be corrupt.

To tackle these issues, the present paper combined SD modeling with the French VIZIR Pavement Distress Assessment Method (VPDAM) to increase stakeholder participation in a new circular economy of road construction and maintenance. The rest of this paper is presented in five sections, including the literature review, theoretical framework, methodology, results and discussion, and the conclusion.

4.2 Literature review

This section reviews the relevant literature on recycling RDW, particularly in the context of Libya. It also reviews the literature showing why SD was used with the French VIZIR Pavement Distress Assessment Method (VPDAM).

4.2.1 Recycling RDW

The construction sector produces much waste due to widespread VM use and institutional barriers to environmental, social, and governance recognition (Abarca-Guerrero, Maas, and van Twillert 2017; Islam et al. 2019; Shooshtarian et al. 2020). VM is used without considering the value of RDW from nearby legal and illegal dumping sites. In some cases, roads are abandoned, and new roads are built nearby. Waste from existing and abandoned roads may serve as RM, and recovered land can be used for future development. In general, building an entirely new road costs much more than rehabilitating or adding new lanes to an existing byway (VTPI 2021). Also, it generally costs more to build roads in urban settings than in rural areas. While recycling should always be an engineering design priority per the IFC pavement management systems (PMS), the issue is exacerbated in densely populated cities where stakeholders must destroy old buildings and roads to make room for new construction.

Despite the demonstrated financial and environmental benefits of recycling RDW, as of early 2021, there are very few laws governing Libya's recycling projects. Contractors have argued that the country's extant laws are out-of-date, and their mandates and powers are perceived as uncertain (Asker, 2019; Jalal Etriki, 2013). Moreover, given Libya's present status quo, there is little compliance with current regulations. Thus, new recycling laws would likely be ignored and ultimately fail (Ali, 2018; Jalal Etriki, 2013).

Researchers studying contractors' misperceptions and corruption in developing nations have argued that many contractors do not understand the professional regulations they must follow. Unfortunately, it is challenging to follow rules and regulations that are poorly understood and managed (Ali 2018; Etriki 2013; OECD 2016; World Bank Group 2020). Worse still, the laws and regulations are outdated and ill-adapted to modern needs. Likewise, construction inspectors' inexperience and lack of necessary training make successful project evaluation a challenge (Asker, 2019; Jalal Etriki, 2013; Khlifa Gana, 2019). Similar studies in developed countries show that even with adequate resources and knowledge, contractors may still be unwilling to comply with recycling laws when there are little to no financial incentives (V. W. Tam, Li, & Cai, 2014; V. W. Y. Tam, Kotrayothar, & Loo, 2009). This problem is more pronounced in developing nations than developed ones. This difference occurs because of the comparative lack of knowledge, training, and infrastructure needed to implement a road construction and maintenance circular economy.

Sadly, war and social unrest are prevalent in many developing nations, causing significant accumulations of hazardous waste. When hazardous waste is mixed with RDW, it becomes contaminated and unusable. Additionally, accumulated RDW interferes with the infrastructure necessary for RDW management. Years of illegal waste dumping have been reported in Libya and culturally similar nations due to liability-evading measures (Negm & Shareef, 2019). Libya's decades-long civil war generated over six million cubic meters of RDW (World Bank, 2020). Moreover, the tragic Port of Beirut explosion in 2020 also released a million tons of toxic waste into the environment, such as pesticides, pharmaceuticals, industrial chemicals, lead from vehicles, and various heavy metals (World Bank 2020).

Financial aid from international donors is often allocated according to economic indicators, with little emphasis on recycling and monetizing environmental impacts via the economic model. A notable effort is the European RE-MED, which partners wealthy donor nations (e.g., France and Italy) with developing nations (e.g., Tunisia, Libya, and Lebanon) to promote sustainable construction practices and expertise-sharing (ENI CBC Med Program, 2020). This type of knowledge and expertise-sharing is uncommon because international donors do not typically consider them economically important.

4.2.2 Combining SD modeling and the VPDAM

To understand the behavior of roads' dynamic parameters, a modeling system is needed with active nonlinear feedback. This system must have some controllable(e.g., rehabilitation policies) and uncontrollable (e.g., the physical environment and equivalent single axle load [ESAL]) factors (S. Fallah-Fini *et al.*, 2010). According to Ruiz and Guevara (2020), the modeling method known as SD assesses dynamic behavior in complicated systems over time. Moreover, SD uses "concepts such as feedback loops, causal loop diagrams (CLDs), and stock and flow structures" (S. Fallah-Fini *et al.*, 2010, p. 3). Furthermore, for Li Hao *et al.* (2008) and Doan and Chinda (2016), SD is a tool for assessing massive, complicated challenges in management (e.g., PMS). SD is also a great tool for analyzing real-world long-term system behavior to increase model validity and the success of decision-making PMS procedures. These processes are achieved using differential equations for identifying causal interactions in feedback loops found in ANNEX I. SD requires original data to determine the model parameters, confirming reliability. Finally, SD involves creating an integrated optimization method to identify effective PMS policies (Fallah-Fini et al. 2010; Ruiz and Guevara 2020a; Sterman 2000).

Notably, CLDs are types of SD models that represent cause-and-effect relationships by mapping closed feedback loops. During CLD development, stakeholders are often involved. Moreover, stock-flow diagrams' (SFDs) simplicity provides a modeling approach that is transparent and accessible to stakeholders. Compared to CLDs, SFDs are more comprehensive portrayals of systems' fundamental physical structures.

Stocks are the numerical amounts of populations, financial accounts, and materials, such as available cash, funds, and debt. Flows represent the stock growth and depreciation rates, such as production, spending, and debt decrease (repayment) or increase (failure to pay). Sterman (2000) argued that "stocks characterize the state of the system and generate the information upon which decisions are based. The decisions then alter the rates of flow, altering the stocks and closing the feedback loops in the system" (p. 102).

Over time, SD has become increasingly popular for engineering management decision-making because it assesses sociotechnical measures. Thus, it can identify the most effective policies that could incentivize preventing road deterioration over more costly reactive practices. This process ensures that SD improves system conditions while lowering costs over the long-term (Guevara *et al.*, 2017; Sterman, 2002).

Abbas and Bell (1994) were right in their prediction that SD will demonstrate its value regarding strategic PMS policy research and development, both regionally and nationally, in cases entailing inter-system feedback and delays. Moreover, SD has been used for transportation and land use systems, supply-chain delays, and air market business cycles (Shepherd, 2014).

Additionally, SD enables easy links between transport models and other sectors (e.g., health, climate, and the economy) while considering feedback and delays over time. These benefits help free growth resources and capacity development (Shepherd 2014; Sterman 2002). Therefore, SD is a suitable approach for this study because it (1) investigates and maps the dynamic nature of road conditions while (2) analyzing the feedback loops' effects on the process of road deterioration.

However, SD has some critical limitations as a mathematical modeling method. For instance, it is unsuitable for large network applications (France-Mensah & O'Brien 2018, p. 5). Moreover, without additional tools, SD can only assess undamaged pavement. Modelers pair SD with road quality assessment tools, such as the Paser Serviceability Index, the VPDAM, and Australian, to resolve this shortcoming. These tools gather data to establish the equivalent single axle load (ESAL) and road quality. Such tools assist stakeholders to maintain safe road conditions for users, augmenting their average pavement life.

Typically, the VPDAM is used (1) in research on road management and rehabilitation (i.e., network and project levels) or (2) when building a road (i.e., a route). In both cases (network or route), it is crucial to correctly identify rehabilitation approaches regardless of whether they are on the same precision levels.

There are two damage categories in the VPDAM: Type-A and Type-B. Moreover, the VPDAM provides a road quality classification scale for both damage categories with three severity levels. Each severity level has three sub-degrees of quality, coming to nine combined. Every damage type is assessed based on two factors: severity and extent (i.e., measurement of the affected road). Thus, the case study's road section is classified as in either very good (Q1-Q2), good (Q2-Q3), fair (Q3-Q4), or poor condition (Q5-Q6), or in need of rehabilitation (Q6-Q7). These damage types are part of the SFD's stocks and flows shown in the methodology section. See ANNEX III, providing more detail regarding the damage type categories.

Another reason that the VPDAM was chosen for this project is that most of the data collection team members are experts in it. Their expertise is likely due to the VPDAM's popularity and accessibility in developing countries like Libya. Ultimately, combining SD with the VPDAM was the ideal choice for this study for three reasons; (1) it facilitated the use of SD on damaged pavement, and (2) the VPDAM is common in developing countries, explaining why (3) the members of the data collection team were VPDAM experts already.

4.3 Theoretical Framework

The present work's sustainable road maintenance system called the virgin-for-used-material-exchange (V4UX) is informed by circular economies and the carrot and stick motivation theory. This section first describes the theories of circular economies and carrot and stick motivation, ending with the V4UX program.

4.3.1 Circular economies

One increasingly common approach to sustainable development for companies and countries is circular economies. Traditional "take-make-waste" linear economic approaches extract or take resources to make products that are later discarded as waste when no longer useful or wanted. For instance, RDW is most commonly removed and discarded illegally on land or in the sea.

Alternatively, circular approaches create economic opportunities while tackling vital natural and environmental resource management concerns. Circular economies minimize waste and pollution by keeping products, materials, and resources in use for as long as possible. For instance, circular economies may use biodegradable waste to create energy, recycle plastic waste to produce new products, and recycle RDW to construct or maintain roads (Guzzo et al. 2022). In other words, circular economies emphasize "reducing or alternatively reusing, recycling, and recovering materials in the production/distribution and consumption process" (Ginga *et al.*, 2020, p. 2).

Ginga *et al.* (2020) also explained that construction and demolition in circular economies have five critical stages, including "preconstruction, construction and building renovation, collection and distribution, end-of-life, and material recovery and production" (p. 2). Notably, the present work deals with all five stages in its proposal of a circular economy approach to creating sustainable road construction and maintenance practices (Delphi Group -Paul Shorthouse 2021; European Commission and Directorate-General 2017).

Two examples of sustainable road technologies used for construction and maintenance include cement stabilization and solidification. These technologies can produce more rigid engineering material by mixing cement-based binders with evenly contaminated waste. This chemically stabilized material can be reused as foundations or rigid road base and subbase courses (Bates & Hills, 2015). Nonetheless, these technologies are rarely used because they require more effort to sustain. For instance, such technologies require a clear commitment by the owner and funding agencies, increased planning and design before implementation, and improved means of identifying and reducing stakeholder reluctance over long-term pavement performance (Bates & Hills, 2015).

Moreover, because prompt RDW recycling is necessary for a circular economy, it is essential to reduce the needlessly long delays between planning a roadworks project and its completion (Bakchan, Faust, and Leite 2019). As explained above, the present paper assumes that it is better in developing countries to encourage timely participation in recycling projects with incentives (i.e., carrot motivators) than with penalties (i.e., stick motivators).

Guzzo *et al.* (2022) asserted that SD is a critical tool for decision-making in circular economy frameworks, as they can navigate these dynamic and complex systems. These authors also explain that circular economies occur at three levels: micro, meso, and macro. Change occurs in micro-level circular economy systems on the individual, household, and organization levels. In meso-level circular economies, change happens due to interactions between actors in systems that share resources (e.g., infrastructure) due to proximity. Finally, change in macro-level circular economies happens across entire regions, nations, and industries.

Additionally, Ginga *et al.* (2020) explained that effective circular economy frameworks require three strategies: narrowing, slowing, and closing resource loops. Narrowing resource loops entails using less material to produce less waste. Conversely, slowing them requires lengthening the use phases (e.g., reusing). Finally, “closing resource loops is the main strategy employed for an effective framework in the reuse and recycling of CDW [construction demolition waste]” (p. 5). This strategy requires recycling materials to make new products. Together, these strategies enable PMS stakeholders to recirculate recovered and recycled material to increase its average life-cycle and reduce pollution. The next subsection proposes a theory for stakeholder motivation to increase participation in the proposed circular economy of road construction and maintenance.

4.3.2 Carrot and stick motivation theory

As described above, a punitive taxation policy is used to solve the recycling problem in Libya. Unfortunately, punitive policies represent the “stick” in the classic carrot and stick motivation theory. Here, the carrot symbolizes a positive motivator, and the stick represents a negative one. Negative motivators often fail because people are pleasure-seeking innovators who, when pushed, will often go to impressive lengths to avoid unpleasantness, such as taxation and fines. However, as pleasure-seekers, people will work hard and often enthusiastically to experience pleasure. Thus, theoretically, a carrot is a much more effective motivator for humans than a stick (Han et al. 2018; Murad Qureshi 2011; Wilson 1996).

Therefore, instead of maintaining conventionally negative motivational tactics in RDW recycling, the present study proposes a new positive stakeholder motivational framework. This framework should effectively motivate RDW recycling because it educates stakeholders on the benefits of successful implementation. Moreover, this framework encourages stakeholders to co-operate for mutual self-interest since everyone “wins” when roadworks projects use RM (Shooshtarian et al. 2020). Another guiding principle behind the proposed framework is to disrupt stakeholders habituated working patterns as little as possible. Since changing habits can be difficult, limiting change for stakeholders should improve their compliance with the new project requirements and guidelines (Borovay 2007; McGuire 2001).

Currently, many contractors are used to dumping RDW beside the new roads they are constructing, as it is quick, easy, and without consequences. While it is possible to implement a system where authorities reduce this behavior using a carrot motivator, it is impossible to punish unknown behavior, like illegal RDW dumping. Moreover, personal allegiances enable people to undermine and circumvent fines in small, community-based, and developing societies like Libya (World Bank Group 2020). Therefore, the present work proposes RDW recycling legislation that considers local traditions and social patterns. This legislation is called the V4UX, which is described in the following subsection.

4.3.3 The V4UX system

The current work proposes the V4UX, a sustainable road construction and maintenance system that promotes stakeholder participation and a circular economy. One of the V4UX's most critical and challenging requirements is stakeholder participation. Fortunately, as explained above, several studies show that it is possible to change stakeholder behaviors and attitudes. This change can be achieved using Ajzen's (1991) theory of planned behavior. Several studies have applied this theory in road management contexts and successfully motivated stakeholder behavioral change (Mak, Chen, et al. 2019; Mak, Yu, et al. 2019; Wu, Yu, and Shen 2017).

Ultimately, for the successful implementation of the V4UX, Libya requires the development of a complete recycling system. As the case study demonstrates, there is no system for managing CDW and illegal RDW dumping in Libya. Therefore, this recycling system must be built step-by-step. The V4UX collects the RDW, recycles it, sells RM and VM, and transports them to construction sites. Moreover, contractors are incentivized through purchase discounts to take the RDW to the recycling center.

In the context of COVID-19, other studies show how people can change their behavior and follow new rules. Specifically, novel behavioral patterns must be introduced in steps (Schultz 2020; Yuan et al. 2012). While it is challenging to produce even minor behavioral changes among stakeholders, it should be achievable if the factors influencing their choices are broken down into simple steps and the changes are as smooth as possible (Eaton et al. 2021). This finding shows that particular motivational tactics and processes can change stakeholder behavior and attitudes.

Since contractors are used to having their materials delivered to them, getting contractors to use RDW may be as simple as having their delivery person drop off salvaged RDW at the V4UX recycling centers to exchange it for RM. If contractors resist this idea, government stakeholders can pick up the RDW from the construction sites, simplifying implementation for contractors. Most importantly, the RM would be available either in exchange for RDW or for purchase at a lower cost than the VM, which is inflated. Having the materials available at the same location should help contractors see the convenience and financial benefit of using less expensive RM over high-priced VM. Moreover, the government must be attentive to local market VM prices to avoid being undercut. Ideally, existing vendors would be made into licensed RM and VM sellers on behalf of the government, providing the same or similar prices as the recycling center. In that case, the only behavioral changes needed are to the contractors since they must use RM in their roadwork projects.

The program would also offer services and discounts that make participation easier and more appealing. For instance, the V4UX would provide lower gas, RM, truck maintenance, and delivery prices to persuade contractors to use this recycling system. This financial savings incentive program minimizes contractors' changes, costs, and inconveniences. These positive incentives are key to a successful V4UX recycling system in developing countries because it is profitable and easy for contractors to comply with.

However, contractors must not be given funding as an incentive because it could be used to buy VM instead of RM, and there is an increased risk of funds misallocation. As another example of corruption and the willingness to exploit and undermine the system, consider how developers sometimes underbid a contract to win. They then complain that there is insufficient money to carry out their contracts and request more money (Anon 2019a). This example is perhaps the most common and challenging form of corruption to eliminate. If the V4UX can eliminate some of it, it may show citizens that corruption is avoidable. As a result, it could help reduce the community or country's general tolerance for this type of corruption and fraud.

Thus, the V4UX is an incentive-based system that creates centralized recycling programs offering RM in exchange for CDW. This process keeps the complicated matter of money out of the system while also reducing the opportunities for corruption. Ultimately, the V4UX will help minimize corruption, illegally dumped RDW, and VM use.

4.4 Methodology

This study relies on triangulated data and research methods, increasing its reliability and validity. The study's research methodology is presented below in five parts: (1) The case study, (2) Data collection, (3) The CLD, (4) The formal simulation, and (5) Model validation.

4.4.1 The case study

A Libyan road rehabilitation project was chosen as a case study to apply the V4UX model. Libya is a developing nation in the North African region with substantial CDW resulting from a decade-long military conflict. Libya also has no construction and demolition waste management records, nor any manuals, guidelines, or policies for their reuse. This lack of direction, record-keeping, guidelines, and policies are caused by Libya's long-standing insular political regime and the country's current unstable government (Ali 2018; Etriki 2013; OECD 2016; World Bank Group 2020).

The present case study involves the maintenance and rehabilitation of two kilometers of a road that crosses from Libya to Tunisia at the Dehiba-Wazin Border (DWB) customs office. The road has no official name, but it is locally known as the "Almarabeh." It is six meters wide, and its entire length is about 18 kilometers. It was initially built between October 2008 and March 2009 and was partially damaged in the 2011 conflict. In 2013, the Altameer Alafriki

Company reconstructed the road (Asker, 2019). The first reconstruction phase began in 2013 and lasted over 36 months due to various delays.

Libya currently has two border crossings with Tunisia. One is located at the Ras Jedir customs office, near the coast. The other is the DWB customs office, along the Almarabeh road. There is much trade between Libya and Tunisia, and most of it is conducted by road. Given the poor condition of the Almarabeh road, most of this trade now goes through the Ras Jedir border crossing instead. The Ras Jedir border crossing usually takes longer to use than the DWB because of its increased traffic. More traffic amplifies the chances of accidents and is more expensive on gas than the DWB. Despite these problems, the Ras Jedir border crossing is preferable to the DWB because it is in better condition, making it easier to drive, less expensive on gas, and causes less damage to vehicles.

Still, trade must sometimes go through the DWB office when the Ras Jedir office is closed. Closures often happen due to increased social problems, particularly during war times. Thus, another objective for the present study is to increase trade in the Nalut region by repairing the 2011 road damage and improving the surface quality of two kilometers of the Almarabeh road.

4.4.2 Data collection

Some of the quantitative data were collected from academic literature and government sources. The qualitative data was attained via interviews, literature reviews, and site visits (Anon 2019b, Anon 2019a; Anon n.d.; Ding et al. 2016; Hongping 2011; Jia et al. 2018).

In 2019, structured interviews were carried out with various Almarabeh roadworks stakeholders in Nalut, Libya. These interviews amassed the required qualitative data to select the appropriate parameters to verify the SD simulation's factors and equations. In 2020, other interviews were conducted with fellow researchers at Concordia University and *École de Technologie Supérieure* (ETS) studying Libyan construction and environmental engineering.

4.4.3 The Causal Loop Diagrams (CLDs)

As previously explained, an SD model was built to better understand the factors involved in implementing the V4UX (Babamiri, Pishvaee, & Mirzamohammadi, 2020). Olson *et al.* (2003) described SD models as “continuous simulation models using hypothesized relations across activities and processes.” One example of SD models is CLDs, which map closed feedback loops, relationships of cause-and-effect. Each variable in Figure 1 represents the major quantifiable variables related to the V4UX’s closed feedback loops.

Additionally, each variable in the CLD is linked by an arrow, indicating the relationship’s direction. Figure 4-1 shows the entire diagram as well as each loop alone, demonstrating how every link begins at the primary variable, which impacts the secondary variable where an arrowhead represents the link’s end. For CLDs, the output of each subloop is a critical phase in the project’s development. In the V4UX’s case, the goal is sustainable roads in developing and developed countries through a circular economy.

Furthermore, each arrow (link) is paired with a polarity sign, indicating either a positive (+) or negative (-) relationship. In a positive (+) relationship, both variables change in the same direction. Thus, when the first variable increases, the second one does too, and vice versa. In a negative (-) relationship, the link represents changes in opposite directions. In other words, when the first variable increases, the second one decreases, and vice versa.

Moreover, there are two types of feedback loops, reinforcing and balancing. Reinforcing loops are self-reinforcing relationships that exponentially compound change in one direction, represented by a central “R.” However, this change can either be growth or collapse. Both growth and collapse can be desirable or undesirable depending on the variable and its context. Indeed, sometimes growth is needed, such as with RM use, the V4UX, and the use of the optimal average percent. At other times, collapse is the goal, such as with VM use, ongoing investment costs, environmental footprint, and corruption.

Conversely, some feedback loops have balancing relationships, represented by a "B." In balancing feedback loops, changes to one variable propagate across the loop, returning the opposite change to the first variable. Thus, when one variable increases in a balancing loop, the effect will pass through the cycle and return a decrease to the first variable. Thus, like a thermostat, balancing loops regulate the processes to maintain a particular state.

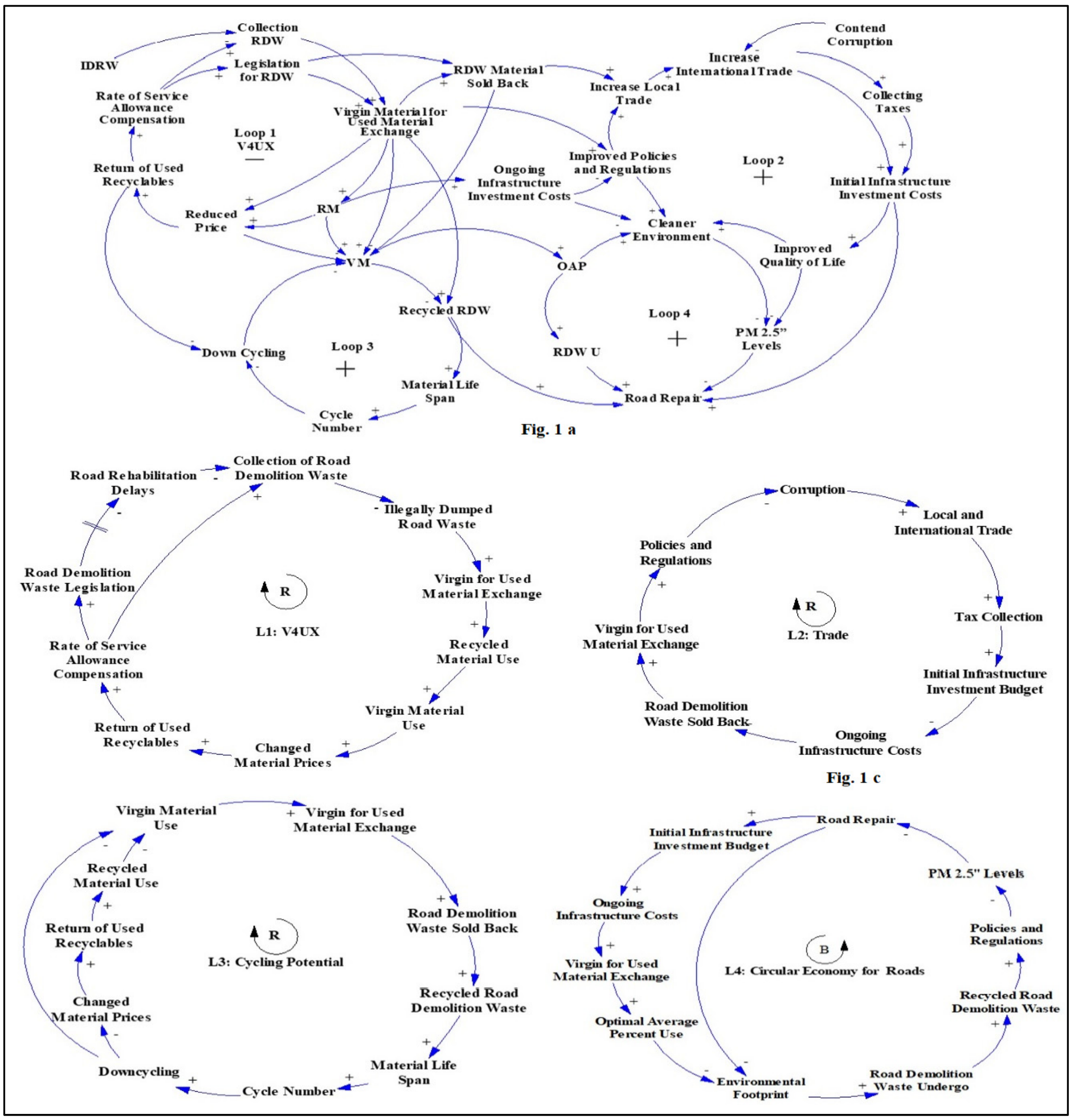

Figure 4-1 Causal loop diagram followed by a simplified diagram of each loop.[1]

For instance, in the context of the V4UX, the CLD model (Figure 4.1) shows that Loop 1 (L1) is a reinforcing loop representing the V4UX program. As the V4UX grows, Recycled Material Use grows too, reducing Virgin Material Use and increasing Changed Material Prices (VM increases while RM reduces). Then, as Changed Material Prices grow, the Return of Used Recyclables also grows, increasing the Rate of Service Allowance Compensation. Moreover, this feedback chain returns better Road Demolition Waste Legislation and increased Collection of Road Demolition Waste. Improved Road Demolition Waste Legislation reduces Road Rehabilitation Delays, increasing the Collection of Road Demolition Waste. Notably, the double line across the link connecting the two previous parameters represents the impacts of delays on rehabilitation.

There are various common consequences when road rehabilitation is delayed, such as increased costs and environmental and social impacts. This feedback chain decreases Illegally Dumped Road Waste, resulting in further V4UX growth. Ultimately, as the V4UX grows, the road's Environmental Footprint reduces, as shown in L4.

Loop 2 (L2) is also a reinforcing loop representing trade in the context of the V4UX. As the V4UX grows, the Road Demolition Waste Sold Back and the Policies and Regulations also grow. Increased Policies and Regulations reduce Corruption, amplifying Local and International Trade. Increased Local and International Trade, in turn, create growth in Tax Collection, leading to a higher Initial Infrastructure Investment Budget and lower Ongoing Infrastructure Costs. Finally, increased Initial Infrastructure Investment Budget and Road Demolition Waste Sold Back decreased Ongoing Infrastructure Costs. This chain of events

[1] Loop 1 (L1) the virgin-for-used-material exchange (V4UX) (b); Loop 2 (L2) trade (c); Loop 3 (L3) cycling potential (d); and Loop 4 (L4)—the circular economy (CE) for roads (e).

leads to more Road Repair and further V4UX growth, ultimately reducing the road's Environmental Footprint (see L4).

Loop 3 (L3) is a balancing loop representing the V4UX's cycling potential. First, increased Virgin-for-Used-Material-Exchange amplifies Road Demolition Waste Sold Back, resulting in more Recycled Road Demolition Waste. As the Recycled Road Demolition Waste grows, so does the Material Life Span, creating a higher Cycle Number and more Downcycling. Finally, more Downcycling reduces the Changed Material Prices and Virgin Material Use. Increased Downcycling and Recycled Material Use result in less Virgin Material Use. As Virgin Material Use shrinks, the Virgin-for-Used-Material-Exchange grows.

Lastly, Loop 4 (L4) is a reinforcing loop representing a circular economy for roads in the context of the V4UX. For optimal performance in a given environment, the optimal average percent of VM must be determined for each project involving RM before this feedback chain begins. Growth in the Virgin-for-Used-Material-Exchange increases Optimal Average Percent Use and decreases the Environmental Footprint.

As the Environmental Footprint decreases, the Road Demolition Waste Undergo (a V4UX program[2]) increases. Next, as the Road Demolition Waste Undergo grows, so does the Recycled Road Demolition Waste, creating growth in Policies and Regulations. As Policies and Regulations increase, PM 2.5" Levels and Road Repair decrease, further reducing the Environmental Footprint. As Road Repair decreases, so does the Initial Infrastructure Budget, resulting in lower Ongoing Infrastructure Costs. Thus, as the V4UX demonstrates its ability to reduce a road's environmental footprint, more road works projects will employ the optimal average percent for improved road sustainability, policies, and regulations.

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[2] This novel program simplifies RDW collection for the government. It also offers financial savings as a clear business incentive for stakeholders to comply with the system. Simultaneously, the system is less susceptible to corruption or difficulties related to fine-collection.

4.4.4 The formal simulation model

An SFD is a representation of the formal simulation model. The SFD is depicted in Figure 4.2, created using VENSIM software and data from Nalut, Libya. The model consists of four parts: (1) stocks -- state variables, reservoirs, and levels; (2) flows -- control variables, processes, and rates; (3) connectors -- arrows; and (4) converters -- translation and auxiliary variables. The model includes nonlinear differential equations about the flows, state variables, levels, parameters, auxiliary variables, conditions, and original values. The level equations represented in Equations 1 and 2 present the system's dynamic behavior.[3]

$$\frac{dXi(t)}{dt} = f(Xi, Ri, Ai, Ci) \tag{4.1}$$

The differential equation is as follows:

$$Xi(t + \Delta t) = Xi(t) + f(Xi, Ri, Ai, Ci) * \Delta t \tag{4.2}$$

These equations can be solved numerically using the Euler software/theorem simulations. These SFDs illustrate the various policies contributing to the V4UX, including the Road Demolition Waste Undergo. In the results section, the principal variables are shown in Figure 4.2.

The original simulation's time settings were as follows: initial time = 0; final time = 36; time step = 0.0625; and time unit = Month. Informed by Yuan (2011), the SFD developed for the present work is depicted in Figure 2. Notably, Figure 2's RDW chain is a system of

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[3] X*i*(t) is a state variable vector w.r.t time while *f* () is a function of vector values. Xi is a state variable, R*i* is a flow variable vector, and A*i* is an auxiliary variable vector. Finally, C*i* is a parameter vector, *t* is a time variable, and Δt changes over time.

codependent actions. This interdependence is a crucial reason for choosing the SD approach to test and develop the V4UX model.

As shown in Figure 4.2, the SFD was divided into three subgroups: G-A, G-B, and G-C. G-A is a model of road rehabilitation activities. There is a long delay between identifying the need to fix a damaged road section and finally finishing the rehabilitation. This model features a negative feedback loop with several delays.

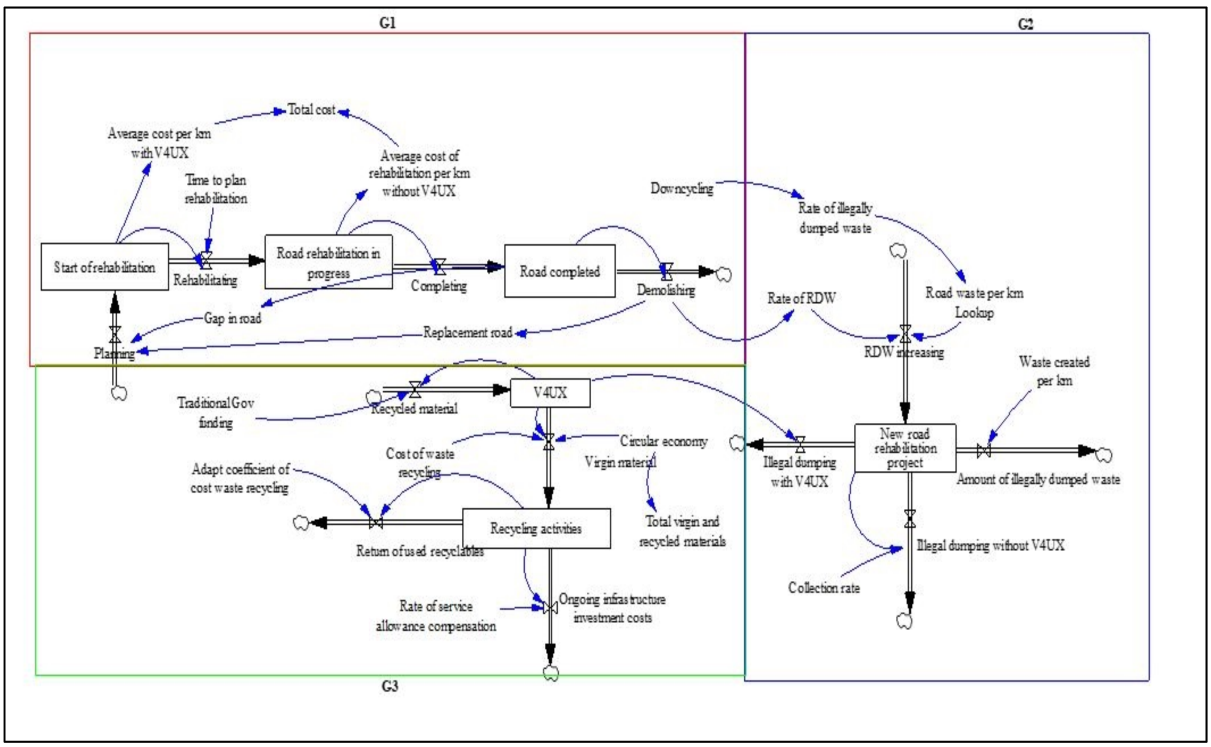

Figure 4-2 Simplified stock-flow diagram [4]

[4] A simplified stock-flow diagram (SFD) showing three groups of interrelated primary and exogenous variables: group 1—the rehabilitation process (red box), group 2—new road rehabilitation projects (blue box), and group 3—the virgin-for-used-material exchange (V4UX) (green box) Legend: G1: group 1, red box; G2: group 2, blue box; G3: group 3, green box

Thus, this part of the model must start in equilibrium. Equilibrium establishes the number of km of road required (e.g., 2 km), which is the initial value for the rehabilitation of km completed. Because of the significant rehabilitation gap, the starting point is zero, so planning is equal to the number of needed replacement km, which, in turn, is equal to the amount of recuperated RDW. Each level is already in equilibrium because of how the other levels are initialized (e.g., Planned Road-KM is initialized equal to planning * time required to plan to build).

Therefore, the model will simulate the road rehabilitation activities without altering any values. Conversely, G-B is a traditional activity for CDW, while G-C aims to link the two groups (G-A and G-B) into one system to find sustainable solutions and implement the V4UX. G-C attempts to show the important elements of the V4UX regarding recycling RDW and illegally dumped RDW.

Next, the components were classified as either endogenous or exogenous variables. Endogenous variables are dynamic and are a part of the feedback loops, while exogenous variables are not influenced directly by the system. L1 represents the endogenous variables and, thus, is of primary importance to this study. Conversely, L2 represents the exogenous variables and is of secondary importance. Nonetheless, it highlights questions that might arise regarding L1's environmental, economic, and social sustainability. Thus, L2 is included in the sustainability score in the long-term.

Like in the CLD, certain values (called "variables" in the Vensim software) in the SFD refer to real-world constants. As constants, the variables maintain the same properties throughout the simulation (Ding et al. 2016).

Some of the proposed SFD's parameters are taken from the academic literature and government sources, including statistics and interviews (Anon 2019a, Anon 2019b; Anon n.d.; Ding et al. 2016; Hongping 2011; Jia et al. 2018). Other values are identified using qualitative approaches, such as interviews, literature reviews, and site visits. The model is also a variable in the V4UX, whose ultimate aims are to reduce corruption and pollution through a circular economy. Another value is the Road Demolition Waste Undergo program, assessed via stakeholder interview data.

4.5 Results and discussion

This section presents the study results and discussion. The first subsection is the analysis of the road's technical systems. The second subsection presents the model testing and validation. Finally, the third subsection explains the policy analyses.

4.5.1 Technical system's analyses

This article combined SD and the VIZIR method, showing that the Almarabeh's 2-kilometer road section's surface is in bad condition. These findings were based on the road's construction records, design, structural capacity, and current and projected traffic.

The road section shows three major types of damage;

1. Cracking, disintegration, and potholes from asphalt aging, hardening, and a poorly draining base.
2. Longitudinal cracking from poor construction joints.
3. Edge cracking due to poor drainage and trucks parking on the roadsides. This damage was caused by water in the pavement that got in through pavement cracks, the subgrade, and into the structure.

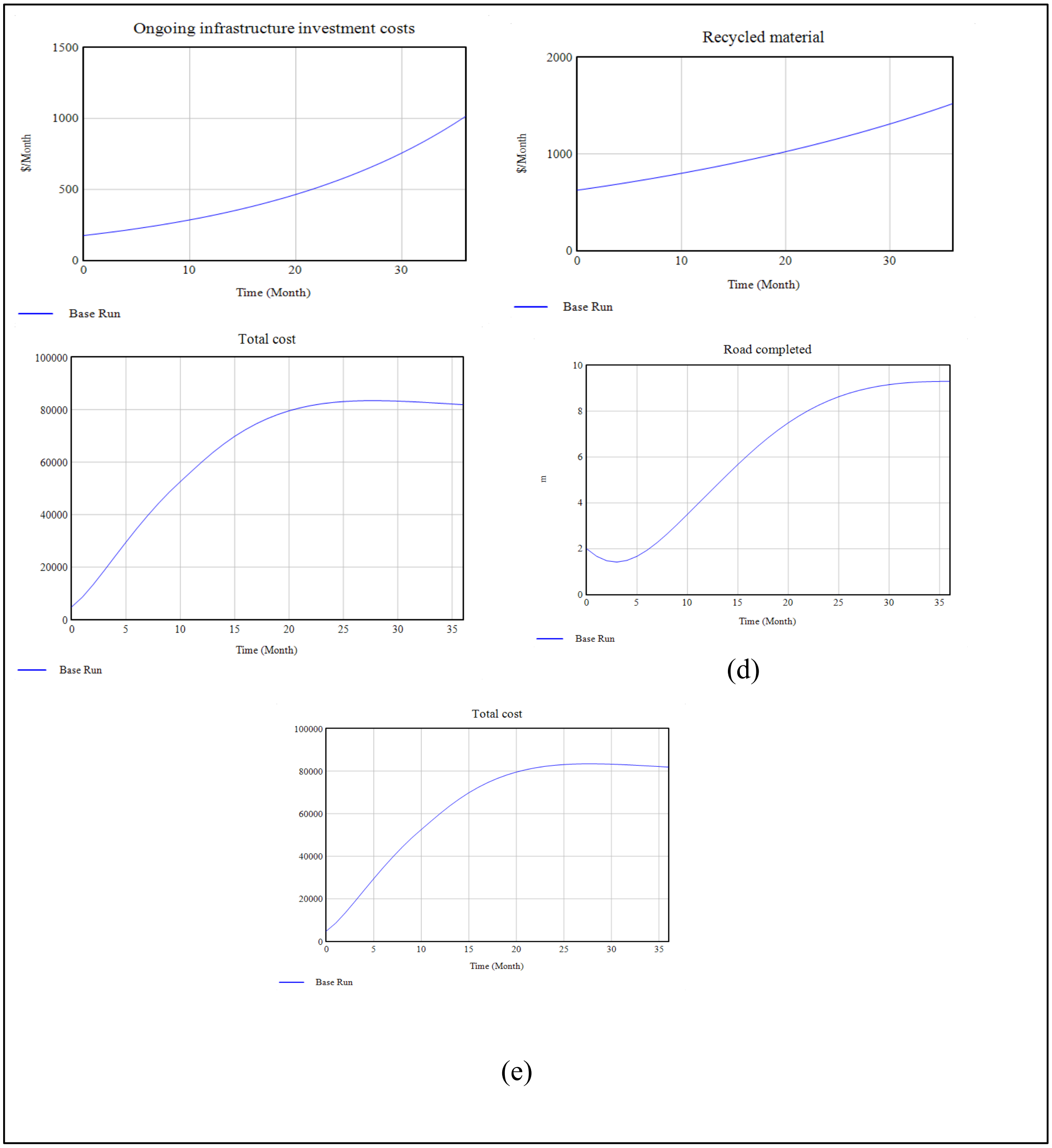

Figure 4-3 Simulation results for the main factors with the base run[5]

[5] (a) increased ongoing infrastructure investment cost; (b) growth of recycled material use; (c) decreased virgin material use; (d) extended project duration; (e) escalated total project cost

Figures 4.3 (a) to (e) show some of the base-run SFD results, supporting the CLD presented in Figure 4.1. In particular, during the study period, the base-run demonstrated increased ongoing infrastructure investment costs, recycled material, roads completed, and the total cost over the study period. Conversely, the base-run resulted in decreased VM use over time.

4.5.2 Model testing and validation

Before the model could be simulated, the qualitative survey data was transformed into quantitative data. Four data conversion methods were used for this task (M3, M4, M5, and M6), helping quantify different qualitative data types (Hongping 2011). As Shiboub and Assaf (2019) asserted, future work is needed to test and confirm the CDW's validity. Therefore, after collaboration and long discussions as a team at ETS, Almadwi and Assaf (2021) ran various laboratory tests to determine hot-mix asphalt's properties when combined with recycled brick powder and virgin limestone powder. These tests were run according to Libya's real-world specifications. The authors demonstrated that, even at 40°C, hot-mix asphalt made with recycled brick powder produces better performance (e.g., less water sensitivity and permanent deformation) than hot-mix asphalt mixed with virgin limestone powder. These improvements result in hot-mix asphalt with a smaller price tag and a longer lifespan.

Moreover, a study by Mohammadinia *et al.* (2017) supports the V4UX model proposed here. The authors conducted resilient modulus tests to show that, although recycled road demolition waste alone does not satisfy construction materials requirements, lime-stabilized road demolition waste with brick powder is an effective and practical material mixture for road construction. Thus, road demolition waste is ideal for roadworks projects when combined with additives, both virgin and recycled.

To build further confidence in the model, tests were run on the data once the qualitative variables were quantified. Testing should confirm the model's accuracy by meaningfully replicating the real-world environment (Hongping 2011; Sterman 2000). However, Forrester and Senge (1980) asserted that no single test can validate an SD model. Instead, SD model confidence steadily accrues with each test it passes and as new similarities are discovered between the empirical reality and model. Still, the primary tests to validate an SD model are verification, validation, and legitimation (Coyle 1983).

Verification tests confirm that the actual system's parameters and structure were accurately copied into the model. Conversely, validation tests check that the model precisely produces the desired behavior in the particular environment it is applied. Finally, legitimation tests assess whether the model obeys the system structure laws and any other relevant, commonly recognized rules. The present study uses all three of these testing approaches.

Furthermore, Coyle (1997) suggests several other parameters that could be used to build confidence in SD models. These parameters are that:

- The CLD must match the problem statement.
- The model should behave as expected.
- The equations must relate to the CLD.[6]
- Dimensional validity must be determined.[7]
- The model should be subjected to extreme conditions.[8]

The present study adopts a dynamic approach to validate the V4UX model. Thus, all five validation tests were run to demonstrate that the proposed model reflects the real-world V4UX circumstances. Results indicate that the model is reliable for use in simulations.

The proposed model was created to replicate the Almarabeh road's actual conditions during the study period, and the model was tested using standard SD methods. Moreover, the study

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[6] Specifically, the equations' "+" and "- "signs must match the CLD's signs.

[7] The variable's dimensions (or units of measurement) on the right of the equation should match the variable's dimensions on the right of the equation.

[8] Extreme conditions tests help determine if a model behaves appropriately.

assumed that traditional pavement technical solutions were used for construction and rehabilitation activities. The road rehabilitation rates were calculated using partial model calibration procedures (Fallah-Fini *et al.*, 2010; Guevara *et al.*, 2017). An assessment tool was used to identify the parameter combination that produces the best fit concerning historical data. This is a common process in SD literature, and it diminished the gap between the simulation results and the actual data.

The proposed model was created using formulations previously used in SD literature to assess road networks. Aging chains, for instance, were used to plan and help the stakeholders to make appropriate decisions for road rehabilitation (Ruiz & Guevara, 2020; Guevara *et al.*, 2017; Fallah-Fini *et al.*, 2015; Sterman, 2000).

Tests were also conducted to confirm that the model's behavior is logical and ensure dimensional and structural consistency. For example, it was ensured that the model's stocks sustain positive values, regardless of the values of the exogenous parameters. We conducted extreme condition and sensitivity tests (Sterman 2000) using the SD modeling software Vensim PLE+ version 8.2.0 to evaluate system behavior under various conditions. See Figure 4.4

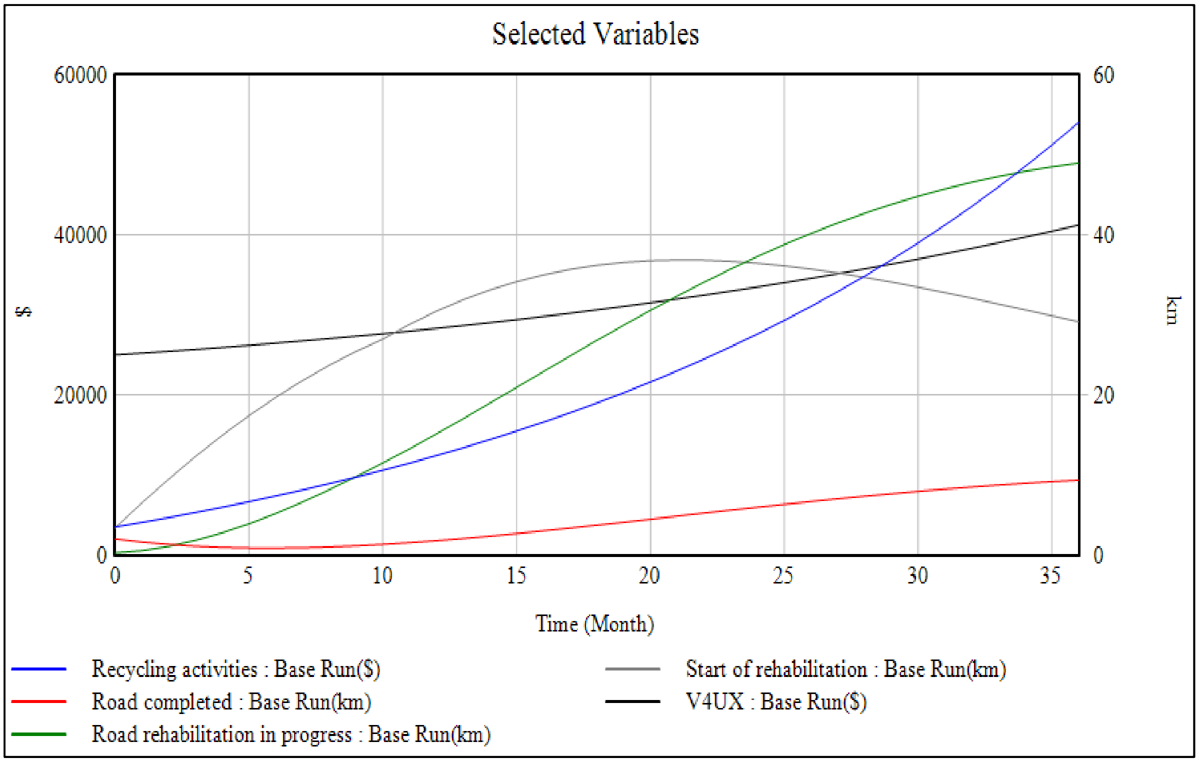

Figure 4-4 Initial stocks values effected by inflow and outflow variables

Each simulation's results show that the parameters behaved logically. For example, their mean values were similar to the historical data from the studies explained earlier. Five variables were used to assess the trend comparison, including the start of rehabilitation, road rehabilitation in progress, road completed, the V4UX, and new road rehabilitation projects. These parameters are based on publicly available data and represent the state of the system. Figures 3(a) to (e) show the simulation results, which are represented by solid lines. Moreover, each parameter's distance was calculated in kilometers-roadway and was acquired via case study data, shown using discrete data points.

4.5.3 Policy analyses

To analyze the present study's policies, counterfactual experiments were run to test what-if scenarios. The policies were defined using a sensitivity analysis, and then the most successful policy of three was identified. The three policies are Policy 1 (P1) Determining the optimal timeframe for road rehabilitation and delays; Policy 2 (P2) Promoting a circular economy of road rehabilitation; and Policy 3 (P3) Uniting optimization and a circular economy. All policies were tested over 36 months, demonstrating the potential outcomes of three scenarios.

When conducting policy analyses, system dynamicists create and test scenarios. Scenarios require the values of specific exogenous parameters (e.g., timeframe for road rehabilitation) to be changed to explore their effects during a period of time. This information helps investigators compare system behavior in different situations over time.
For the present study, the baseline scenario (when no interventions are made) is 14 months, the scenario with the most delays is 24 months, and the scenario with no delays is 12 months. These test scenarios are also used to determine P1, revealing the most effective period for road rehabilitation and delays.

4.5.3.1 The sensitivity analysis to define policies and Policy 1: determining the optimal timeframe for road rehabilitation

This study used the following value groups (baseline, over-baseline, and under-baseline) to simulate different time spent on road rehabilitation and delays. The first value is 14 months, which is the baseline according to the project contractor (Asker, 2019). As shown in Figures 4.5 (a) to (c), the over-baseline values include 16, 18, 20, 22, and 24, where delays start increasing the total costs at 16 months and 24 months is the worst-case scenario. Finally, the under-baseline value is 12 months, which produces the highest number of roads completed, the smallest amount of ongoing road rehabilitation, and the lowest total costs. These three groups of parameters allow stakeholders to simulate different amounts of time spent on road rehabilitation and delays to determine the most effective option.

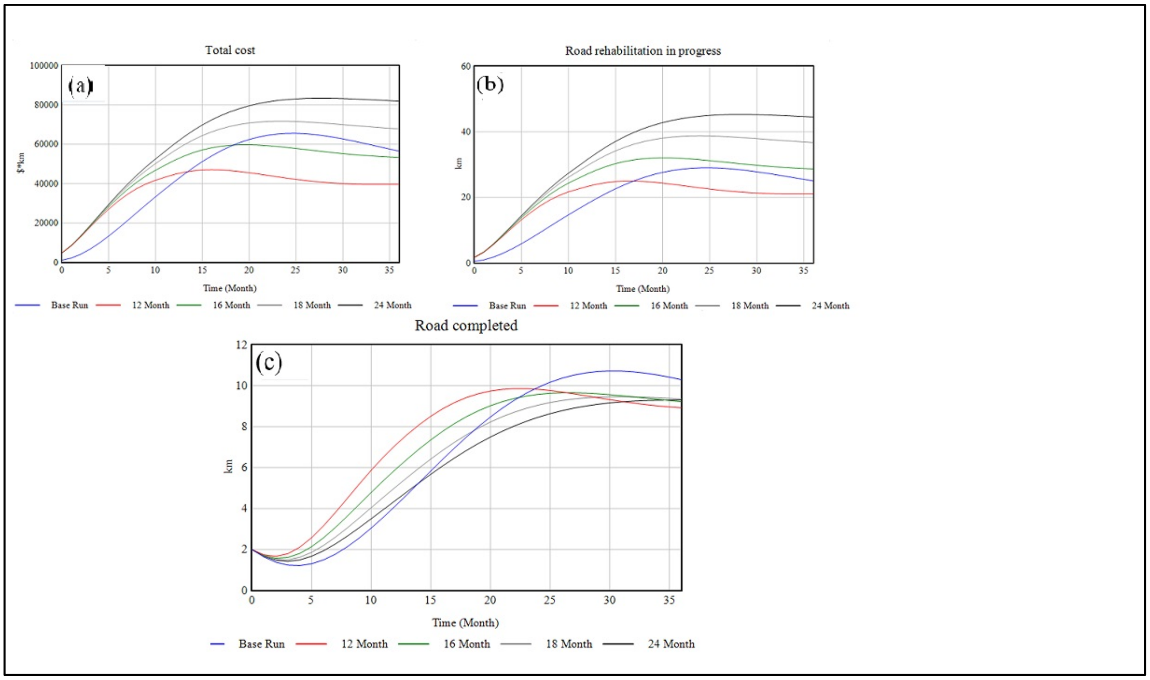

Figure 4-5 Sensitivity analyses simulated change in cost over time

Additionally, Figures 4.5(a) through (c) show that the riskiest policy is to allow road rehabilitation and delays to last 16 months or more. This policy significantly increases the road's total cost, so the best strategy is to cut out delays. Doing so means ensuring that road rehabilitation takes no more than 12 months to complete. This reduced timeframe diminishes the total cost and road rehabilitation in progress while increasing the number of roads completed.

4.5.3.2 Policy 2: Promoting a circular economy

The purpose of P2 was to discover the effects of promoting a circular economy of road rehabilitation. To attain a circular economy, this policy encouraged stakeholder participation in the V4UX program. Results show that stakeholder participation and the road condition ameliorated when P2 was implemented. Although the cost savings are not exceptional, Figure 2.4(a) shows a slightly higher initial investment that peaks mid-study period, dips a little, and then levels off. This result shows that, after 30 months, there is a uniform distribution of total costs over time. This finding avoids the need for excessive early investments.

Roads completed was the highest and had the lowest total cost with a 12-month timeframe compared to the rest, including the base-run. Therefore, increasing the number of rehabilitated roads also entails reducing delays and the number of ongoing rehabilitation projects. Fewer delays in 12 months cause higher initial costs and emitted GHG that will reduce and level off by the end of the study period. In general, the findings show that governments should prioritize maintaining road sections in bad condition, avoiding delays. This policy enables stakeholders to shrink emissions and costs while keeping the roads in excellent service condition for longer. These findings inspired P3, described in the following subsection.

4.5.3.3 Policy 3: Uniting optimization and a circular economy

In summary, P1 determined that the optimal timeframe policy for road rehabilitation and avoiding delays is 12 months. P2 showed how the V4UX promotes a circular road construction and maintenance economy. P3 was created to attain better results by combining P1 and P2, simultaneously modifying the following parameters: sustainable rehabilitation percentage, RM and ongoing infrastructure investment costs, and time to rehabilitate roadways.

Specifically, P3 adheres to the optimal timeframe policy of 12 months and promotes a circular economy of road construction and maintenance practices. First, its values were adjusted to between the baseline values of almost half to all, the latter representing top-level system benefits. Additionally, like in P1, the time to rehabilitate roads was increased from 14 to 24 months and decreased from 14 to12 months. Figures 2.4(a) to 4(c) compare the baseline to the alternative timeframes.

Overall, P3 demonstrates that the best costs and stakeholder participation levels are achieved in 12 months of road rehabilitation and delays. Decreasing the maintenance rate diminished costs and emissions by roughly half. This relationship exists because the GHG declines as the roads improve and contrarywise. These changes encourage ongoing sustainable road construction and maintenance, which is necessary for a circular economy. In the end, P3 shows how governments can achieve a circular economy by creating sustainable infrastructure policies and assessing various parameters simultaneously.

4.6 Conclusion

Previous studies on road waste management have focused on its various stages, but they do not generally consider stakeholder response. To fill this literature gap, this study explored whether positive incentives (e.g., financial savings) can motivate private and public stakeholders to participate in a circular road maintenance economy, the V4UX. Combined with other studies (e.g., Almadwi & Assaf, 2021; Mohammadinia *et al.*, 2017; and Yuan *et al.*, 2012), the present study's findings strongly support the proposed V4UX model's validity using SFDs.

SD successfully shows how savings linked to recycled RDW use in the V4UX model could change stakeholder behavior (e.g., getting them to recycle RDW and use RM). The SD model also illustrates how promising the V4UX's road demolition waste undergo program is. Ultimately, the V4UX program is shown to produce less illegally dumped road waste and lower dependence on VM for new construction and rehabilitation. Findings show that stakeholder receptivity to RDW recycling programs like the V4UX is very important to their successful implementation.

The program achieves increased stakeholder participation by reducing the costs and inconvenience to stakeholders (e.g., by requiring less change by stakeholders). Increased stakeholder involvement reduces the program's environmental footprint (see Pellecuer, Assaf, & St-Jacques, 2014). Overall, the present study demonstrates how the V4UX program has been successful for the Almarabeh roadworks project in Nalut, Libya. Due to its success, this program will be applied to the remaining 16 km of the Almarabeh road. Indeed, Asker (2019) reported that the road will undergo this rehabilitation over the next few years.

Using the case of Libya's Nalut region, the present study shows that illegal dumping of RDW is a serious and broadly harmful hazard that can be reduced through the V4UX. A large body of research reveals very few legal landfill sites in underdeveloped countries like Libya. Moreover, the few legal landfill sites that do exist are inadequately operated. Combined with other environmental circumstances (e.g., the lack of recycling laws and dumping sites and much political unrest) means that most Libyan RDW dumping is illegal. Regardless, both landfilling and illegal dumping have a negative environmental and social impact.

For successful implementation, the V4UX program requires active engagement from all stakeholders, particularly at the local government level. This study shows that, over time, the V4UX model motivates stakeholder participation. It achieves this participation by reducing the costs of each project phase, including RDW collection and RM distribution. Additionally, the model reduces illegally dumped RDW and corruption, two major roadblocks to achieving a sustainable road system. Finally, because the project minimizes stakeholder change, it is more likely to motivate stakeholder compliance than a more conventional approach.

Once the project is fully implemented and evaluated in Nalut, the V4UX can be adapted for other countries, especially developing ones. Applying the V4UX worldwide would be of enormous social, economic, and ecological benefit due to the ever-increasing stress caused by accumulating RDW, especially illegally dumped RDW. However, the findings presented here would benefit from further validation and other case studies showing new parameters for simulation improvement.

CHAPITRE 5

SYSTEM DYNAMIC MODEL FOR SUSTAINABLE ROAD REHABILITATION INTEGRATING TECHNICAL, ECONOMIC, AND ENVIRONMENTAL CONSIDERATIONS

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ABSTRACT

This paper develops a System Dynamics (SD) model to identify the best road strategies maintenance and rehabilitation on the network level, considering its technical, environmental, and economic grounds. This model uses triangulated research methods, such as interviews, government data, policy analyses, and the French VIZIR Pavement Distress Assessment Method (VPDAM), integrated into an SD model. The SD determines and allocates maintenance budgets given a set of environmental and operational conditions. The system is then tested on a case study at the Radès Road Port (RRP) in Tunisia. Baseline analyses of the simulation show the networked effects of key factors, such as increased greenhouse gas (GHG) emissions, rehabilitation deficits, and climate change with reduced average pavement life (APL). The SD model is calibrated and validated using data from RRP rehabilitation operations from 2020 until 2040. The model is coupled with an optimization module that recommends optimal rehabilitation operations. Specifically, this paper recommends three pavement solutions for the RRP and three pavement management systems (PMS) policies for improved sustainability. The model is sound based on technical principles, resulting in enhanced road function, sustainability, and cost savings. These findings contribute to literature in PMS, SD modeling, sustainable development, and engineering management

5.1 Introduction

Preserving transportation infrastructure is challenging because, over time, extant roads and highways deteriorate, requiring routine, periodic rehabilitation interventions (Guevara *et al.*, 2017). These interventions are difficult for road agencies to address because of budgetary constraints at the local, state, and federal levels (Commission 2009). These limitations usually result in delayed maintenance and rehabilitation, causing the accumulation of yearly backlogs (Jenn *et al.*, 2015). The accumulated road damage accelerates road aging, increasing the costs of reactive rehabilitation measures.

These challenges are often exacerbated in developing countries since most do not have regulations and technical standards for sustainable road construction and rehabilitation and typically rely on those of developed countries with different environments. Consequently, poor management, incomplete technical diagnoses, absent environmental and social analyses, and unsuitable technologies and standards result in biased findings. This chain of events leads to inadequate interventions and poorly performing investments with questionable internal rates of return.

This study uses the city of Rades, Tunisia, as a case study for sustainable road rehabilitation solutions, since the Tunisian Road Administration (TRA) is attempting to implement timely preventive measures against road degradation. Unfortunately, in a system of perpetual delays and financial constraints, agencies like the TRA tend to fix roads at the lowest initial cost regardless of the solution's sustainability. Stakeholders' goals generally include short-sighted cost savings, so they often use the cheapest available short-term solutions. However, short-term solutions do not repair structural damage or address top-bottom cracking in the asphalt, which inevitably reproduces up into the new asphalt surface (Soro 2020). This process often results in poorly estimated construction budgets, worsening road conditions, and increased production of road waste, illegal landfilling, and future rehabilitation expenses (Ghibaudo 2018; Soro 2020).

As Tunisia's leading shipping container facility, the Radès Road Port (RRP) handles 75% of the inbound and outbound exchange. The RRP also handles around 20% of Tunisia's national freight traffic (~6.28 million tons) and 57% of its port traffic (OECD 2019). In 2020, the Millennium Challenge Corporation (MCC) introduced a broad rehabilitation program to update and restore

Tunisia's RRP network operations (WSP 2020a, 2020b). As the RRP's paved network of roads develops, the focus will gradually shift from new road construction to maintenance and rehabilitation. Therefore, it is necessary to provide RRP stakeholders (e.g., contractors, policymakers, agencies, private companies, and NGOs) a guide or tool for determining the most sustainable, efficient, and cost-effective rehabilitation solutions.

To address the above issues in the RRP region, this paper combines assessment and modeling methods integrating the interdisciplinary topics of climate change, pavement design and performance, and the economics of road rehabilitation into holistic and sustainable pavement solutions. Based on accurate existing data, the results show that a sustainable development strategy in the RRP region can be achieved by adjusting the materials used to rehabilitate pavement to ensure increased cost savings and longevity. Ultimately, this process should assist stakeholders in identifying the best fit between asphalt and concrete from technical, economic, and environmental perspectives, particularly for heavily trafficked pavements built on weak soils in the Mediterranean climate. The rest of this article is organized into four sections: literature review; methodology; results and policy analysis discussion; and conclusion.

5.2 Literature review

The following literature review describes the CDW management literature on sustainable development and climate change. The next subsection analyzes empirical studies on System Dynamics (SD) modeling and the VIZIR Pavement Distress Assessment Method (VPDAM). Finally, the section ends with a description of the knowledge gaps in the reviewed literature that this study aims to fill.

5.2.1 Sustainable development and climate change in CDW management

Another dimension of road maintenance and rehabilitation is sustainable development, particularly in the context of climate change. Liu (2004) argued that there are six critical elements for an effective sustainable development strategy: (1) stable and high employment and economic growth; (2) effective environmental protection; (3) efficient use of resources; (4) social progress that meets everyone's needs now and later; (5) strong government-stakeholder cooperation, and (6) regular program evaluation. Over the last few decades, sustainable development "has become an important international and national concern to integrate economic, environmental, [and] social considerations in sustainable planning" (Liu, 2004, p. 1). Research shows that developing countries wishing to cultivate sustainable CDW management must create and enhance sustainable development systems, both legislative and institutional (Ali 2018; Etriki 2013).

Environmental sustainability is directly related to climate change and its effects on networks of roads and their construction, rehabilitation, and maintenance costs. Mallick *et al.*, (2014) show that both the short and long-term effects of climate change (e.g., shifts in air temperature and increased rainwater, ocean levels, and occurrences of category 3 hurricanes) on road functioning, maintenance, and rehabilitation, especially in coastal areas, are substantial, cumulative, and costly.

Given mounting construction costs and diminishing funds, pavement maintenance and user operating costs must be optimized against different climate change scenarios. Optimization necessitates reliable data on the projected effects of climate change on pavement function and lifespan.

5.2.2 SD modeling and the VPDAM

Road deterioration, maintenance, and rehabilitation are dynamic "behaviors" operating within a nonlinear feedback system, meaning that they interact with a variety of environmental and technical conditions in complex ways. To understand how these processes, behave, an equally dynamic model must be used to simulate and predict both the road conditions and how the roads change over time. Such a model would include controllable factors, such as rehabilitation strategy, as well as uncontrollable factors including equivalent single axle load (ESAL) and the physical environment. System dynamics modelling is an effective tool for the simulation of road deterioration because it can account for the nonlinear feedback loops of the interactions between conditions, effects and behaviors of roads (S. Fallah-Fini *et al.*, 2010). Ruiz and Guevara (2020) explained that SD is a modeling method for assessing dynamic behavior in complex systems over time "using concepts such as feedback loops, causal loop diagrams (CLDs), and stock and flow structures" (p. 3). Moreover, Doan and Chinda (2016) and Li Hao *et al.* (2008) described SD as a tool for analyzing massive and complicated management challenges, like with PMS. SD can also be used to assess real-world system behavior over the long-term to help users increase model validity and the effectiveness of PMS decision-making processes. This process is achieved using differential equations for identifying causal interactions in feedback loops**.** SD requires original data to estimate model parameters, ensuring model reliability. It also relies on an integrated optimization method for determining effective road maintenance policies (Ruiz and Guevara 2020a).

CLDs are SD models that map closed feedback loops, representing a cause-and-effect relationship. Stakeholders are often involved in SD when developing CLDs. Moreover, the simplicity of stock-flow diagrams (SFDs) provides a transparent modeling approach accessible to stakeholders. SFDs are more detailed representations of a system's underlying physical structure. Stocks are the numerical amounts of materials, populations, and financial accounts, such as available funds, cash, and debt. Flows are the rates of stock growth and depreciation, such as spending, production, and debt repayment or increase. In general, "stocks characterize the state of the system and generate the information upon which decisions are based. The decisions then alter the rates of flow, altering the stocks and closing the feedback loops in the system" (Sterman, 2000, p.102). SD is increasingly used for engineering management decision-making via the assessment of sociotechnical measures to determine the most effective policies that incentivize the prevention of road deterioration over more costly reactive practices. This, in turn, improves system conditions and reduces long-term costs (Guevara *et al.*, 2017; Sterman, 2002).

As Abbas and Bell (1994) predicted, SD has demonstrated its value regarding strategic policy research and development at regional and national levels in cases involving inter-system delays and feedback. Shepherd (2014) explained that SD has been used to analyze land use and transport systems, business cycles in the air market, and supply-chain delays. As well, the approach allows transport models to be easily linked to other sectors (e.g., climate, the economy, and health) while considering time delays and feedback. Ultimately, these benefits help liberate capacity development and growth resources (Shepherd 2014; Sterman 2002). Hence, SD is a suitable modeling approach for the present study because it portrays the dynamic nature of road conditions while accounting for feedback loops influencing the physical road deterioration processes.

However, SD is limited in that it is a mathematical method unsuitable for broad road network applications (France-Mensah & O'Brien 2018, p. 5), since it lacks more detailed physical road distress evaluation methods. To remedy this limitation, road quality assessment tools (e.g., VPDAM, the Paser Serviceability Index, and Australian) can be used to collect data on physical road conditions and equivalent single axle load (ESAL). This allows for more accurate SD modelling of physical road conditions better reflecting the environmental conditions it seeks to analyze and predict. As well, these physical assessment tools assist stakeholders in keeping roads in safe conditions for users and increasing average pavement life (APL).

To investigate cases like the RRP's deteriorated road network, this study combines SD with the VPDAM to account for the extensive rehabilitation required, which must be prioritized over maintenance. The VPDAM is typically employed in road rehabilitation and management research (i.e., network and project levels) or when constructing a specific road (i.e., a route). In both cases (network or route), it is crucial to properly identify rehabilitation approaches regardless of whether the precision levels are the same. Thus, SD is combined with the VPDAM to predict Rades Road's future conditions and estimate the appropriate costs, tools, and timeline for road rehabilitation.

In particular, the VPDAM identifies two categories of damage: Type-A and Type-B. It also provides a scale of road quality classification for each category of damage according to three severity levels, each with three sub-degrees of quality (nine in total). Each damage type is quantified by two factors: extent (i.e., length of road affected) and severity. In the present study, the road sections' condition is classified as either very good (Q1-Q2); good (Q2-Q3); fair (Q3-Q4); poor (Q5-Q6); or in need of rehabilitation (Q6-Q7). These damage types are part of the SFD's stocks and flows, found in the methodology section. Each road section is classified in one of these five stocks at any given moment. See the ANNEX VI, which describes the damage type categories in more detail.

Moreover, the VPDAM was also selected for this project because most of the data collection team for the RRP road rehabilitation project are experts in the method, which is easy to access in developing countries. Therefore, combining SD and VPDAM was the best choice for the present study since (1) it enabled us to use SD modeling on a damaged road and (2) VPDAM is accessible in developing countries (including Tunisia), which is why (3) the data collection team members were already experts.

5.2.3 Knowledge gaps

Shepherd (2014) argues that there is a dearth of research on transportation modeling. Future research should investigate freight and port development, competition dynamics, and system and transport demand sensitivities to varying external factors regarding demographics, the economy, and modeling behavior (e.g., at the user or stakeholder level).

Few studies use empirical data to validate results predicting future road performance and maintenance requirements. There is also a considerable research gap in the study of climate change's influence on pavement performance and average pavement life. Furthermore, a limited number of studies (1) integrate sustainability into their road construction and maintenance policies, and (2) triangulate research data and methods (e.g., SD combined with VPDAM). Indeed, Mallick *et al.* (2014) argued that the study of sustainable development requires interdisciplinary and triangulated research engaging both pavement engineering and climatology. Finally, Kang *et al.* (2020) pointed out that few studies use SD to investigate the performance improvement of government building structures (i.e., schools) and budget allocation. Thus, the SD model proposed in this study accounts for existing historical and projected climate, environmental, economic, and road quality data.

5.3 Methodology

This section describes the study's research methodology and consists of three subsections. First, we describe the research framework, then the data collection. The last subsection is the SD model, presented in two parts: (1) an explanation of how the model was designed and (2) a description of the proposed model.

5.3.1 Research framework

This paper's overarching research question is: How can the best sustainable intervention strategies for rehabilitating degraded pavement be determined at the technical, economic, and environmental levels? To answer this question, this study uses triangulated data and research methods which increases their validity and reliability.

A comprehensive SD model was created to determine the most efficient and cost-effective rehabilitation strategies at the network level for paved roads in coastal Mediterranean climates. SD and VPDAM are combined to project the possible climate change impacts on pavement degradation over 20 years in Mediterranean ports. The SD model determined and allocated maintenance budgets given a set of environmental and operational conditions. Together, these strategies accurately reflect the road network's environmental, economic, and technical data.

The system was tested via a case study of Tunisia's Rades Road Port. Baseline analyses of the simulation show the networked effects of key factors, such as increased GHG emissions, rehabilitation deficits, and climate change with reduced average pavement life. The SD model is calibrated and validated by comparing historical data taken from previous studies (explained in the following sections) and projected RRP rehabilitation operations data from 2020 to 2040. The model is coupled with an optimization module that recommends optimal rehabilitation operations.

5.3.2 Data collection

To achieve optimal pavement design, construction, and maintenance, Pellecuer *et al.* (2014) identified four kinds of essential quantitative road condition data : traffic, climate, receptor, and road. The current study gathered all four types. The traffic data consists of cumulative traffic volume, average vehicle speed, percentage of heavy vehicles, and annual average daily traffic (AADT). The receptor data consists of the road sections' linear population density and the distance from the road to the receptor. Next, the climate data includes average precipitation, temperature, and wind direction and velocity. Finally, the road data includes geometric characteristics including the number of traffic lanes and road section dimensions sourced from local road agencies. Other road data includes pavement characteristics (e.g., texture, distress, roughness, surface age, and deflection) determined using VPDAM methods based on pavement management units (ERA 2013; Ghibaudo 2018; RDA 2014).

Secondary quantitative data sources include the World Bank (*Plan quinquennial de développement de la Tunisie*, 2011), the Tunisian OECD Competition Assessment Reviews (OECD 2019), the Tunis-Carthage Meteorological Station (2001-2020), and the Tunis-Carthage Airport Meteorological Station (Windfinder.com 2020).

The study also included qualitative data, such as stakeholder interviews and two government reports. These two reports were prepared by Williams Sale Partnership Limited (WSP, 2020a, 2020b) with the first interviewee's participation. The first interviewee was the *Directeur d'Entretien à la Direction Générale des Ponts et Chaussées au Ministère de l'Équipement, de l'Habitat et de l'Aménagement du Territoire* (MEHAT) of Rades, Tunisia. The Director conducted much of the two studies that provided the present work's quantitative data, including setting up the field data collection process, determining the necessary statistical analyses, and drafting the reports (WSP 2020a, 2020b). Other Tunisian and Canadian road agency experts were also interviewed, including a soil characterization specialist, two infrastructure and civil engineers, and an environmental specialist.

These reports were based on the design and construction records from the Radès Logistics Zone (RLZ) and the road's current projected traffic. The SD model was developed by the authors of the current study based on this information, as described in the next section. Once all the data was collected, it was analyzed to inform the SD model's construction. The model was first designed qualitatively using a CLD and then quantitatively using SFDs. Finally, the simulation and calibration of the model were accomplished using data from eight road sections from the RRP road.

To further improve pavement rehabilitation processes, the optimal solution and strategy for the road's evolution were used on one of the RRP's road sections called "RR33." The RR33 is high-traffic, approximately 730 m long and 15 m wide, and was chosen based on its deteriorated condition. This cross-section has significant rutting as its primary form of damage. The case study's purpose is to demonstrate the proposed SD model's capacity and validity over the projected 20 years of analysis

(2020-2040). For further detail on the RRP network sections, see ANNEX VI. Ultimately, the reports show the need to reinforce the road by adding material thickness or stabilizing the port land. The pavement distress data from the current study indicate significant pavement failure and warn stakeholders of more impending failures, similar to the above WSP reports.

5.3.3 The SD model

This section has two subsections. The first explains how the SD model was designed, while the second presents the proposed model.

5.3.3.1 Designing the model

The SD model was designed based on extant literature (e.g., Mallick *et al.*, 2014; Norhidayah *et al.*, 2017; Saeideh Fallah-Fini *et al.*, 2010; WSP, 2020a, 2020b) and triangulated data on climate change, pavement material properties, characteristics, distress, and roughness conditions. This data was collected from primary (interviews) and secondary (publicly available) data sources. The integrated model was then calibrated with observation data from eight RRP road sections of different ages with comparable characteristics and properties. This step was coupled with an optimization module that identifies the lowest cost rehabilitation and maintenance strategy over the road's life-cycle established at 20 years.

To ensure that coming generations are protected from anticipated climate change, improved road construction and design are needed to increase pavement resistance to the adverse effects of climate change. Pellecuer *et al.* (2014) and Soro (2020) argued that the polluting emissions from road production significantly add to the damaging effects of global warming. Therefore, designers and decision-makers face a significant challenge when selecting a pavement design between continuous reinforced concrete pavement (CRCP) and asphalt concrete (AC) pavement.

Thus, the present work proposes a novel data-based approach for selecting a pavement surfacing design between CRCP and AC, especially for roads with heavy traffic. The paper uses a holistic SD assessment to optimize Tunisia's available sustainable pavement design and construction resources.

5.3.3.2 The proposed SD model

This subsection describes the proposed SD model's CLD and SFDs. Figure 1 is a CLD representing the dynamic relationships between the SD model's four main feedback loops: (1) the physical environment, (2) technical systems, (3) economic activities, and (4) sustainable pavement solutions. These four loops show the road system's deterioration and maintenance dynamics at the aggregate level.

5.3.3.2.1 The CLD

Notably, since road deterioration and maintenance physics are complex processes, the equivalent feedback structure is comparatively complicated. Recall that CLDs map closed feedback loops that represent cause-and-effect relationships. Arrows represent the links between CLD variables and show the direction of the relationships. Figure 5.1 shows how each link begins at the first variable, affecting the subsequent variables and ending with an arrowhead at the final variable in the sequence.

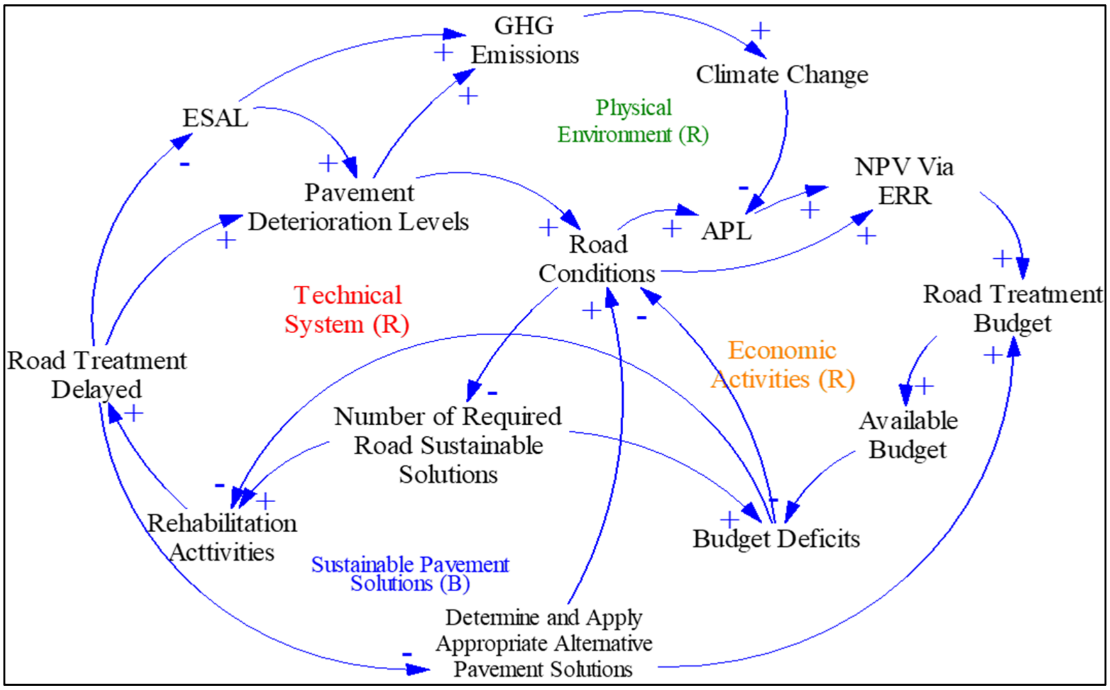

Figure 5-1 The CLD relationships between the main parameters[9]

To properly assess the outcomes of the CLD (Figure 5.1), its three subloops are treated as one. Indeed, any given subloop's output is a necessary step toward the whole. The arrows (links) are paired with either positive (+) or negative (-) polarity signs, indicating the nature of their relationships. Positive relationships change in the same direction. Thus, as the first variable increases or decreases, the second one does too. Negative relationships change in opposite directions. Changes to the first variable result in opposite-direction changes to the second.

Finally, feedback loops are either reinforcing or balancing. Reinforcing loops compound change in one direction, represented by an "R." This change can either be growth or collapse, which can be desirable or not given the context and variable. On the other hand, balancing loops are represented by

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[9] (1) the physical environment, (2) technical system, (3) economic activities, and (4) sustainable pavement solutions.

a "B," and they regulate processes to maintain a particular state. Changes to one variable spread across the loop, resulting in an opposite change to the original variable.

The red loop is called "Technical System," which describes the road's technical aspects. This loop has various interacting parameters. Specifically, as traffic levels increase, so do pavement deterioration levels, reducing road conditions, average pavement life, the economic rate of return (ERR), and net present value (NPV). As road conditions worsen, there is an increased need for more sustainable road maintenance solutions. However, this results in increased budget deficits and rehabilitation activities, resulting in road treatment delays, causing greater pavement deterioration and traffic (i.e., road use), reducing the road's average pavement life and NPV, and increasing GHG emissions. In the end, this loop is reinforcing and describes how road authorities' rehabilitation operations negatively affect road use and deterioration levels.

Next, the purple loop represents "Economic Activities." The average pavement life, NPV, and ERR drop as road conditions worsen, leading to a lower estimated road treatment budget, fewer rehabilitation activities, and worse road conditions. Thus, this loop is reinforcing and demonstrates the impacts of inadequate road treatment budgets on rehabilitation delays, leading to increasingly worse road conditions and budget deficits.

The green loop called "Physical Environment" shows that as traffic and pavement deterioration levels rise, GHG emissions also increase, leading to more climate change (e.g., worse meteorological events and weather patterns). Higher climate change and pavement deterioration levels result in poorer road conditions, a shorter average pavement life, and a reduced NPV and ERR. Therefore, this is another reinforcing loop, demonstrating the impacts of pavement deterioration and traffic on climate change and road conditions.

Combined, these three reinforcing loops represent a cycle of damage to all variables and the overall road maintenance system. Traffic load, environmental conditions, and other deterioration factors contribute to pavement deterioration and worsening climate change. Thus, the fourth loop was created, which acts as an intervening loop to balance these relationships and create a more sustainable system.

The fourth loop is blue and is called "Sustainable Pavement Solutions." This balancing loop proposes pavement solutions appropriate to the feedback system described above. First, as more alternative pavement solutions are identified and used, road conditions improve, resulting in a higher average pavement life, NPV, and ERR. These changes reduce the need for more sustainable construction, maintenance, and rehabilitation solutions. As a result, this loop reduces the rehabilitation budget, budget deficits, climate change, and road treatment delays. Ultimately, improved road conditions from sustainable pavement solutions benefit entire systems through improved sustainability.

5.3.3.2.2 The SFD

The SFD model designates the RRP's dynamic behavior by considering the number of road sections in very good, good, fair, and poor conditions. It also assesses the total user costs on RRP roads in fair and poor condition. Figure 5.2 demonstrates the simplified model of road rehabilitation, conditions and quality (Q1-Q2, Q2-Q3, Q3-Q4), dynamically replicating road deterioration processes. As road deterioration progresses, GHG emissions rise, and the average pavement life drops. A complete list of the model equations for the SFDs can be found in ANNEX VI (Equations S [1-77]).

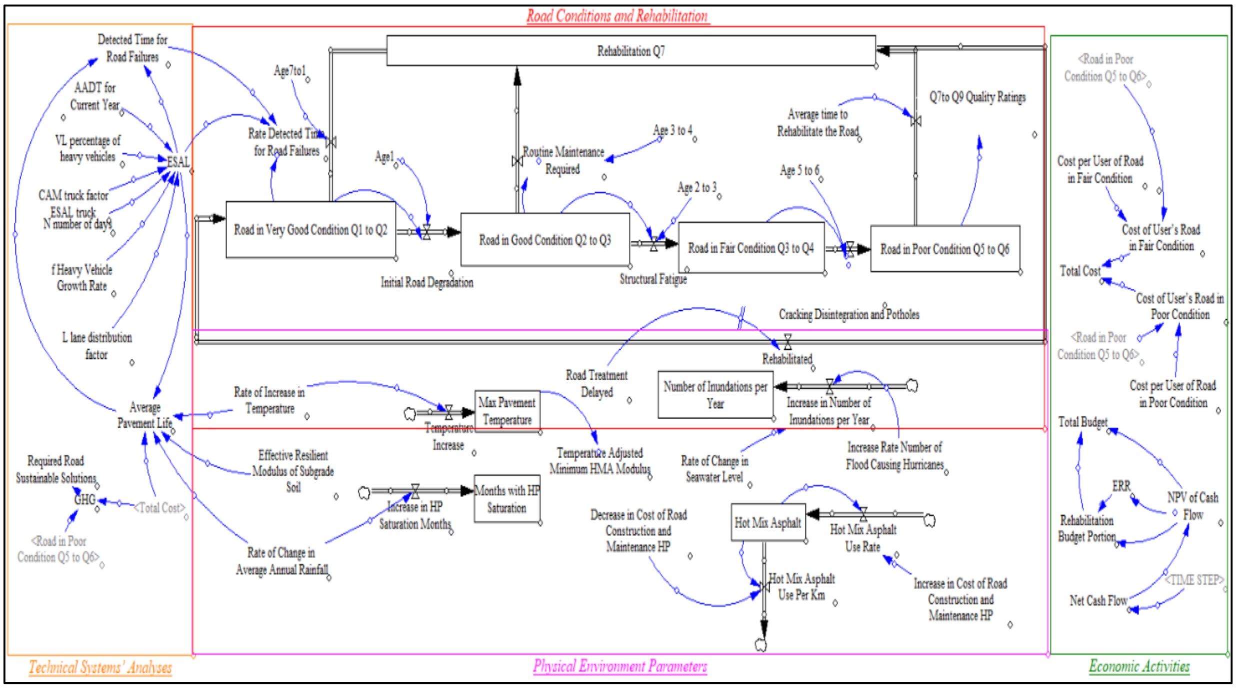

Figure 5-2 Simplified SFD with primary and exogenous variables.

Throughout the SFDs in Figure 5.2, various shadow variables are shown in gray and encased in angle brackets to reduce crossing arrows, maintaining order while ensuring that all the analysis components are fully interrelated.

The model computes system conditions over 20 years, from 2020 to 2040. Figure 5.2 shows the SFD's segments and their interrelationships, which are based on the main components of the CLD, as shown in Figure 5.1. The SFD design matches the most important CLD parameters, including average pavement life, detected time to road failure, ESAL stocks and flows, budget, and road user costs on fair and poor roads.

The SFD model uses ESAL to represent stock change rates and flows regarding road conditions. As each stock's flows and rates change, the variables indicate preservation (maintenance or rehabilitation) or deterioration (superficial or structural). These flows occur either within or between the aging chains. The SFDs use the percentage and the temperature in Celsius for several environmental parameters, such as the Historical Normalized Monthly Average Temperature (MAT) and the Historical Normalized Monthly Average Rain (MAR). These parameters were calculated with a hundred percent

(HP) saturation adjustor for the maximum number of months and temperature. Money represents the economic parameters, such as NPV, ERR, total costs, and user costs.

For instance, the model's top-left quadrant demonstrates the main element's (ESAL) relationships with other variables, such as how it influences road quality and the detected time for road failures. The model's far left, middle quadrant shows the various inputs used to calculate the average pavement life, such as total budget and ESAL. This part of the model allows stakeholders to simulate the impact of changes to those inputs on the total and user costs. User costs are expected to be increased on roads in fair and poor condition compared to roads in very good and good condition. This is due to the reduced speed required while traveling on such roads combined with more accidents, fuel spending, and damage to vehicles. Thus, by reducing the number of roads in fair and poor condition through rehabilitation, user and total costs will decrease over time.

Moreover, the top center part of the system reproduces road sections' quality and associated rehabilitation behavior. The "Age #" variables define the number of years that an ESAL remains in a stock, and Table 5.1 shows the initial values of the RRP's stocks for 2020, represented in kilometers influenced by amounts of ESAL. Additionally, the model can be used to identify the best ways to rehabilitate roads in fair and poor condition. These sustainable rehabilitation activities keep roads in very good and good condition as long as possible.

Table 5.1 Initial values of the RRP's ESAL stocks for 2020

Road conditions stocks	**Initial values ESAL (km)**
Rehabilitation Q7	50
Road in Fair condition Q3 to Q4	200
Road in Good condition Q2 to Q3	100
Road in Poor condition Q5 to Q6	60
Road in Very Good condition Q1 to Q2	40

The SFD's bottom left to center represents climatic condition stocks and flows. Four factors representing climate change were considered: (1) rising air temperature that increases pavement temperature resulting in a decreased hot-mix asphalt (HMA) modulus; (2) rising rainwater levels affecting the length of time that the subgrade soil will be close to or at saturation point distressing the subgrade soil modulus; (3) rising ocean water levels; and (4) growing amounts of Mediterranean tropical-like cyclones, often called "medicanes." Factors 3 and 4 are anticipated to escalate flooding, lowering the subgrade and HMA. Therefore, the present paper uses four climatic variables: ocean levels, medicanes, air temperature, and rainwater. To evaluate the effect of these climate change variables on the RRP's average pavement life, the pavement structure was assessed using various subgrade moduli values and temperatures.

Finally, the road sections' cost parameters are found in the bottom right quadrant of Figure 5.2. The costs are calculated via three primary variables including total costs, GHG emissions, and user costs for roads in fair and poor condition.

5.4 Results and discussion

This section presents and analyzes the findings. First, the road system's technical systems' analyses are described, including the physical environment, pavement solutions, and economic activities. Then, the four policy analyses are conducted: (1) the sensitivity analysis to define the policies, (2) Policy 1: Determining the optimal budget allocation and average time to rehabilitation, (3) Policy 2: Promoting maintenance over rehabilitation, and (4) Policy 3: Combining budget optimization and maintenance.

5.4.1 Technical systems' analyses

This paper determined that the eight selected pavement section surfaces are in poor condition according to SD and the VIZIR method. These findings were based on the road's design, construction records, current and projected traffic, and the existing pavement's structural capacity. This damage is characterized by three main types: (1) edge cracking caused by poor drainage and trucks parking along the road; (2) cracking, disintegration, and potholes from asphalt aging, hardening, and a poorly draining base; and (3) longitudinal cracking in the middle of the road from poor construction joints.

The observed damage is caused by water entering the pavement through cracks and suction from the subgrade into the structure.

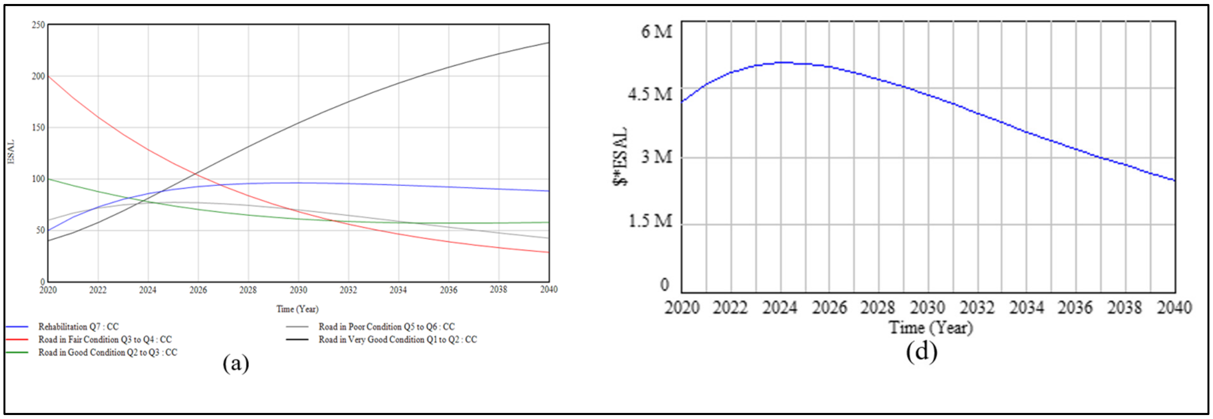

Figure 5-3 Baseline of road conditions based on available budget

Figure 5.3(a) shows the baseline behavior in which the parameters behave reasonably, confirming their validity. Over 20 years, the model increased the number of km in very good condition, decreasing the roads in fair condition. Moreover, as the number of km in very good condition increases, so do the ESAL impacts of the rehabilitated roads. Finally, Figure 5.3(b) represents total road rehabilitation costs for the study period, showing that they were reduced from a maximum of approximately $5 million in 2024 to $2.5 million by 2040. Conversely, in ANNEX VI, Figure A-III 3 shows the number of km rehabilitated each year, and that rehabilitation flow depends on the available budget, as shown in the CLD and the SFD. Finally, Figure A III 3 shows how the model allows stakeholders to calculate user costs and that they were reduced over 20 years on roads in fair condition due to increased rehabilitation.

As shown in Figure 5.2 the present work proposes a quantitative model of road deterioration using an SFD. The SFD was validated on the RR33 road section, chosen because it is in the worst condition of all the RRP's road sections. The RR33 road section consists of four layers from surface to base: a 60 mm coating of standard AC, a 120 mm layer of AC, a 200 mm granular base, and a 300 mm crushed stone subbase. Other RRP road network sections are also four layers but with slightly different properties. From the top to the base, their layers include 60 mm of standard AC, a layer of 140 mm AC, and 200 mm each of base and subbase.

This study conducted a detailed mechanistic examination to determine the RR33 road sections' existing pavement's structural capacities. The HMA use rate per 2-lane km was calculated based on the three ESAL equations provided later in this section. In the next section, we describe each individual group of parameters.

The proposed model also allows stakeholders to simulate changes in the parameters used. This capability enables them to find the optimal parameters for a sustainable PMS. For example, suppose the company changes the average time to rehabilitate the road from 1 (base-run) to 0.5 or 1.2. In that case, we obtain the results in Figure 5.4.

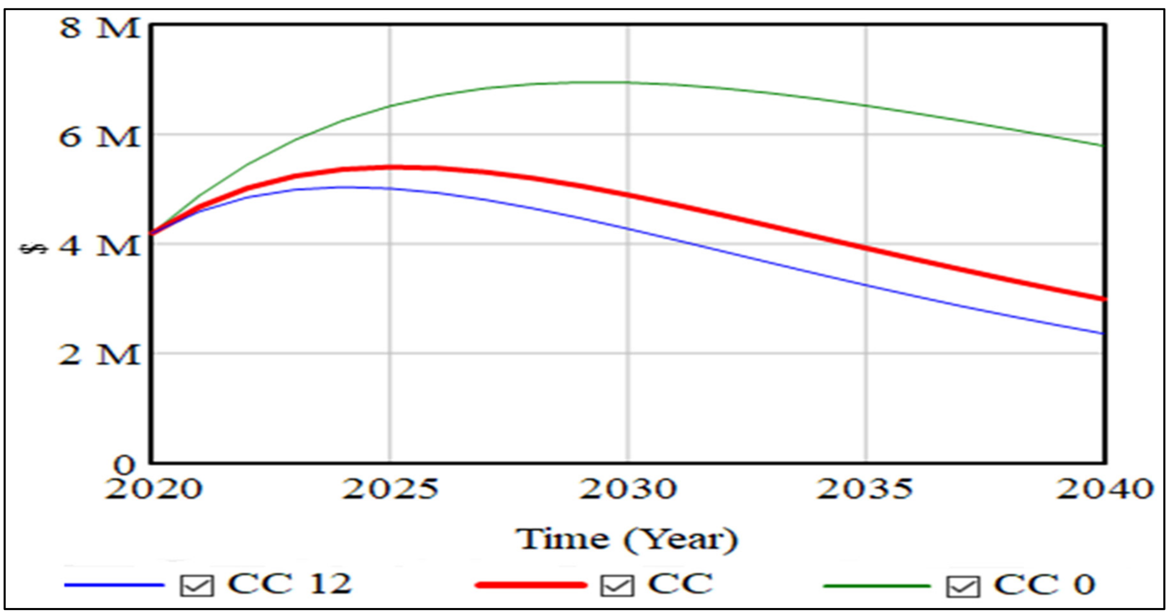

Figure 5-4 Total costs for the base-run (CC) compared to alternative costs

Figure 5.4 shows that the total costs reduce over time for all three simulations, including the base-run (CC) and the two alternatives (CC 12 and CC 0). Notably, the costs are the lowest for simulation CC 12, likely because the average time to rehabilitate is the lowest. These results indicate the need to reinforce the road system through either additional material thickness or stabilization (see subsection

5.4.1.2). Like the WSP, the present work was conservative in estimating the cumulative traffic over 20 years to be 100 million ESAL for the RR33 road section. The simulation confirmed that the RR33's estimated ESAL is close to the real data, confirming its validity. The results were calculated considering the road's transit traffic, the development of the RLZ, and the projected RRP extension (see Figure A III-3). The ESAL will steadily decrease after 100 million ESAL, the highest point. This decreased ESAL represents a drop-in road conditions over time, reducing the user rate and ESAL. These findings were later used in the structural capacity assessment of the proposed pavement design.

Additionally, the cumulative ESAL over the study period was further calculated for the RRP extension only. This calculation was based on the number of twenty-foot equivalent units (TEUs) per year; the projected annual traffic growth; and a truck factor equal to 1, as estimated in the EGIS-group report (WSP, 2020b). The results are shown in Table 5.2.

Table 5.2 Cumulative ESAL over 20 years for both scenarios.

Scenario	**TEU in 2040**	**Annual traffic growth**	**Cumulative ESAL over 20 years**
Base	650,000	3%	10.2×10^6
Aggressive	910,000	5%	12.0×10^6

According to the EGIS-group report (WSP, 2020b), the cumulative ESAL for the study period is about 100 million. The existing pavement's structural capacity assessment and proposed solutions require estimating the cumulative ESAL over the next 20 years. That calculation was based on Equation 3.1 below:

$$ESAL = AADT \times V_{hv\_lane} \times CAM \times n \times f \times l \tag{5.1}$$

See the description of equation variables in ANNEX IV. For the RR33 road section, the ESAL calculated using Equation 5.1 was found to be 2,628,000 ESAL/year. Also, the cumulative traffic per year (λ) of ESAL was calculated as follows:

$$\kappa = \frac{\left((1+\alpha)^{year} - 1\right)}{\alpha} ESAL \tag{5.2}$$

Where: α is the traffic growth rates. Equation 5.2 results are represented in Figures 5.5(a) and (b). For the other road sections in the RRP, the yearly ESAL was determined to be 1,095,000, while the ESAL for 20 years of cumulative traffic was found to be 100×10^6 million.

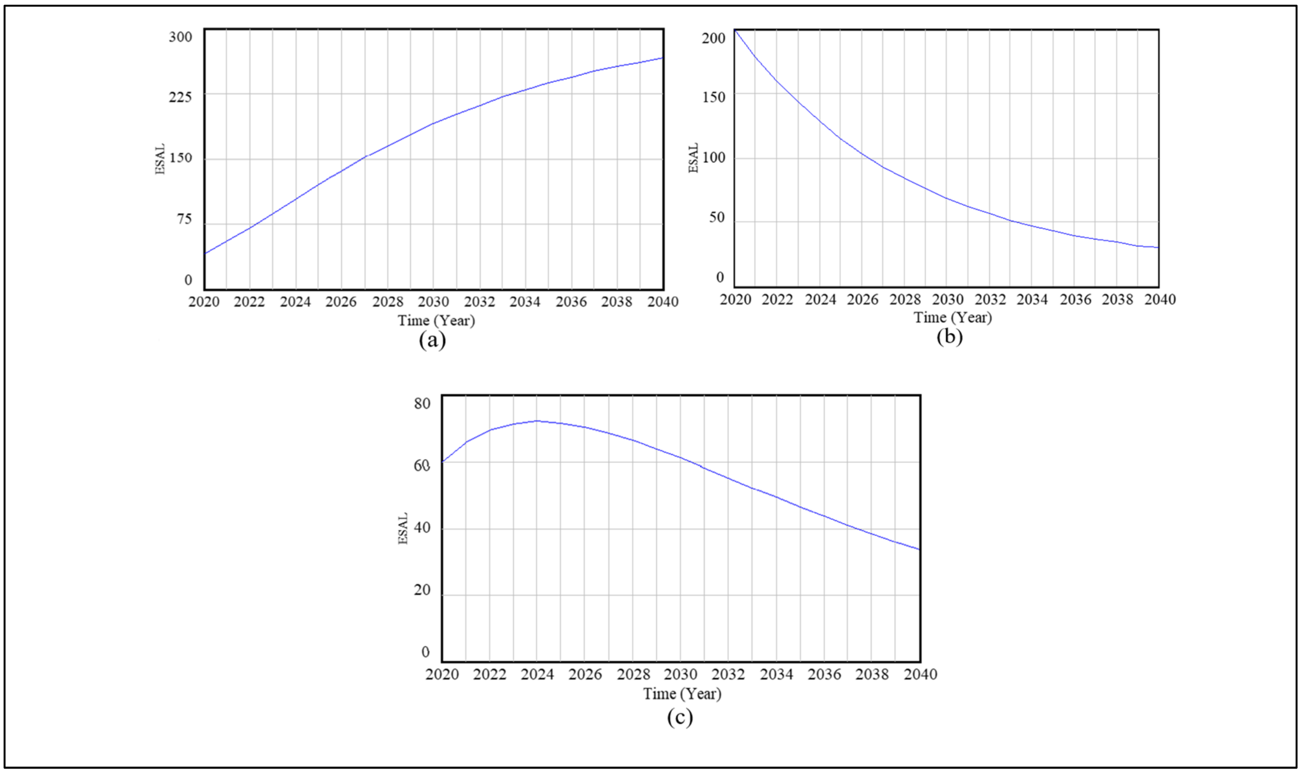

Figure 5-5 Result of road conditions[10]

[10] (a) Very good road conditions, (b) Fair road conditions and (c) Poor road conditions over time.

Results shown in Figures 5.5 (a) to (c) indicate that, after rehabilitation in 2020, the road will stay in very good condition until 2036. However, after 2036, the RR33 will need immediate intervention (see Figures 5.5[a], [b], and [c]). To avoid causing long-term negative effects of accumulated deterioration, the road should be restored via maintenance by 2036. Conversely, pavement that is in good and fair condition (see Figure 5.5[b]) will likely require maintenance from 2022-23, 2027-33, and again in 2039. When the traffic load reaches the highest values from 2020-23, the stakeholders must manage the ESAL. In 2030, according to the estimations, the traffic will increase until 2040, but it will not reach 100 million again. If it goes over 100 million, rehabilitation is needed.

5.4.2 Physical environment

This subsection provides an overview of the RLZ's climatic conditions. First, the RLZ's baseline meteorological conditions are shown to accurately describe the project's environmental setting. This is followed by a summary of the projected impacts climate change would have on road conditions in the area. Four factors representing climate change were considered: (1) rising air temperature that increases pavement temperature resulting in a decreased HMA modulus; (2) rising rainwater levels affecting the length of time that the subgrade soil will be close to or at saturation point, distressing the subgrade soil modulus; (3) rising ocean water levels; and (4) a growing number of Mediterranean medicanes. Factors 3 and 4 are anticipated to escalate flooding, lowering the subgrade and HMA.

Therefore, the present paper uses four climatic variables: ocean levels, medicanes, air temperature, and rainwater. Tunisia has a Mediterranean climate with relatively mild winters and hot summers (See Figure A III 5 and 6) . The pavement structure was assessed using various subgrade moduli values and temperatures to evaluate the effects of climate change on the APL of RRP's eight road sections. (See Figure A III 7 (a-d)) show how 20 years of projected climate change affect the RRP's pavement. For example, increased maintenance costs were determined and partially explained by the increased HMA thickness required to maintain the deteriorated roads. Successful rehabilitation paving is limited to only the portions of road that need repair to control the maintenance costs and enable road use to continue with minimal delays. Conversely, rehabilitation costs and road use delays will escalate as the road portions requiring maintenance grow in number and size.

Results indicate that, over 20 years, climate change (e.g., more inundations and higher air temperatures) will result in increasingly hotter pavement temperatures, shortened APL, damage to the road surface, and diminished effectiveness of subgrade modulus. For instance, Figure A III 7 (a) shows that the RRP's maximum pavement temperatures are expected to increase by approximately 1.5 % during the study period. Moreover,

Figure A III 7 (b) shows an expected 1.5 % rise in the RRP's air temperature. Another prediction is a 1.5 to 2.4 increase in the number of floods per year (Figure A III 7 [c]). Finally, Figure A III 7 (d) shows that, after its highest point in 2026, the APL will decrease by 2040. The APL's decline is due to cumulative damage caused by unfavorable climate influences on crucial pavement material properties (e.g., the moduli). Therefore, similar to Mallick *et al.* (2014), one of the present paper's critical discoveries is that alterations to these important climate factors have a significant negative impact on pavement functioning and deterioration over time. Additionally, Figure 5.6 shows that the number of months the soil is expected to be at or close to saturation increases from 1 to 4 months over 20 years.

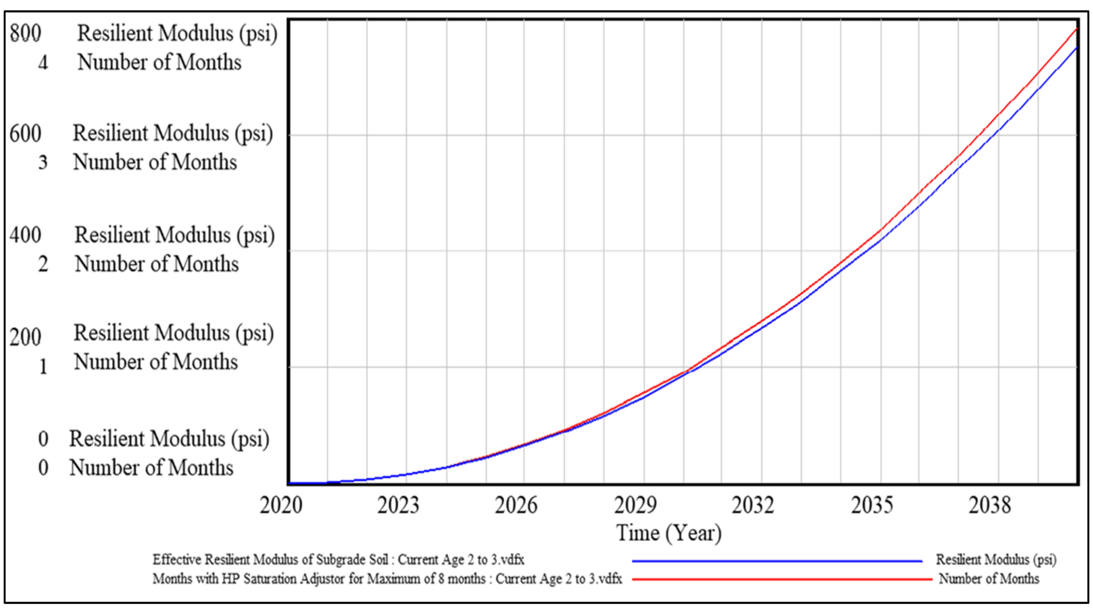

Figure 5-6 Combined effects of factors influencing pavement damage cost increases with and without climate change.

The corresponding change in effective subgrade soil resilient modulus is from 5 psi to roughly 800 psi. These findings are similar to Mallik *et al.*'s (2014) results, supporting the paper's conclusions.

5.4.3 Pavement solutions for the RR33 road sections

Given the SD simulation results and RRP's conditions, this paper considers three pavement solutions for the RR33 road section. The first solution is a thick and rigid HMA alternative, consisting of polymer-modified asphalt, compacted concrete and granular base course assessed using the VPDAM. The second is a thinner, high elasticity "Rigid Pavement Alternative C" (WSP, 2020a). From surface to base, it consists of polymer-modified asphalt plus fiber; a base course of reclaimed cement; and a weak capacity subbase. The third solution is a high elasticity "Flexible Pavement Alternative D," from surface to base consisting of conventional asphalt, a base course of reclaimed cement, and a weak capacity subbase.

Because of the significant traffic volume differences between the RR33 and the RRP's other road sections, the three intervention alternatives were adapted to the other sections by varying the AC surface layer thickness to conform with structural design requirements. (See Figure A III 8). The second option, rigid pavement alternative "C," was determined to be most appropriate for RR33 based on environmental, economic, and physical considerations. This alternative was chosen given its reclaimed cement base course, relatively low cost (see subsection 5.4.1.3), and sufficient ESAL tolerance.

5.4.4 Economic activities

This subsection presents the economic activity analyses, including the total budget and ERR for each road section and pavement solution, as well as the NPV. The consolidated economic analyses for the SD model are based on two main sources. The first is the output of the SD model simulation conducted by the author of the current study. It shows (a) pavement condition evolution over the 20-year analysis period; (b) discounted and undiscounted benefits of vehicle operating costs and time and maintenance savings; and (c) the quantity of vehicle polluting emissions during the pavement use phase. The second is a safety cost-benefit analysis and projected RRP container traffic for the next 20 years based on WSP report analyses(2020a). For further detail, the policy analysis section (5.4.2) introduces how the above cost-benefit analysis can impact road rehabilitation.

Traffic projections consider the ESAL on the RRP extension, rehabilitation operations, and increased transit traffic within the RRP's zone of influence, especially to and from the East Industrial Petroleum Port zone. These projections also show market share growth over time. This paper draws traffic data projections from WSP reports (2020a; 2020b). According to report data analyses, the base or "normal" scenario of projected container (TEU) traffic growth is 3%, while the worst-case "aggressive" scenario of projected TEU traffic is 5% (see Table 5.2 for further detail). Given its marginal traffic levels and adequate structural capacity, RR33 has only one empirically justified intervention – the rigid pavement alternative C. Moreover, the obtained ERR is roughly 22% and 35% at the 3% and 5% traffic growth rates, respectively (See Table-A III 1). In other words, no additional capacity is needed. Notably, the reported ERR is elevated since the present ERR is about 3.8 m/km. Therefore, the technique reduces the IRI considerably (to 1.2 m/km) while diminishing the operating costs for vehicles.

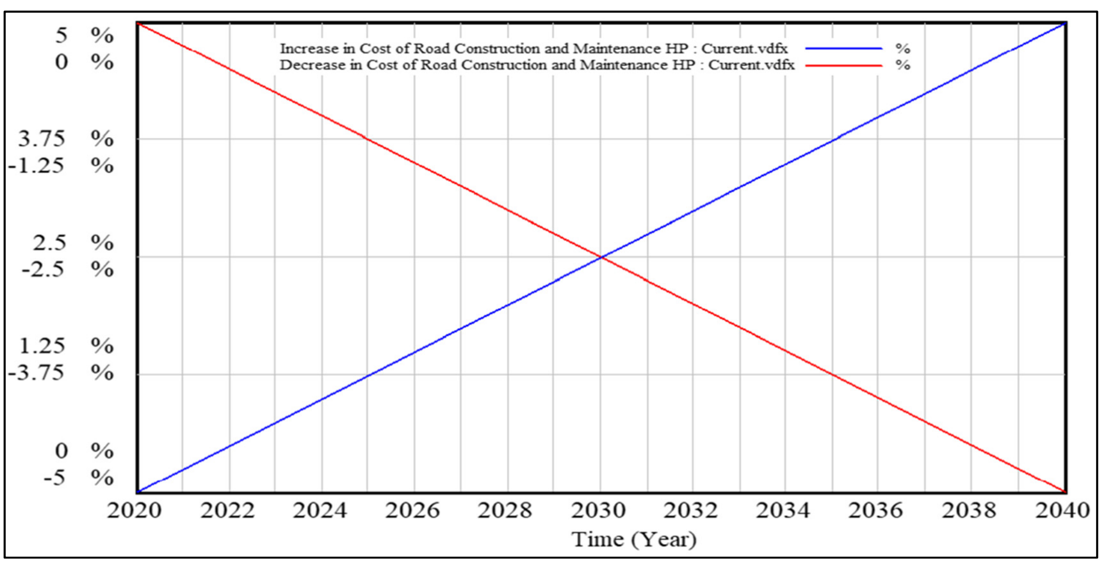

Figure 5-7 Cost of road construction and maintenance with climate change

Figure 5.7 reflects the combined effects of all of the findings for the 20-year study period with and without considering the impacts of climate change. There is an expected cost increase of 50% by 2040 when climate change effects are not accounted for early on in pavement rehabilitation strategy. Conversely, there is an anticipated 50% decrease in overall rehabilitation cost when planning for the effects of climate change.
Ultimately, Figure 5.8 shows how the present SD model links climate change to pavement rehabilitation and cost savings.

In ANNEX III, Figure A III 9 (a) shows that roads in fair condition have a maximum user cost of approximately \$1.8 million in 2025, dropping to \$700,000 by 2040. Conversely, the top user costs on roads in poor condition are expected to reach roughly \$3.75 million in 2025, then drop to \$1.8 million by 2040. This shows that user costs are higher on poor condition roads than fair condition roads, so the alternative pavement solutions reduce user costs over time.

Furthermore, Figure A III 9 (b) presents the NPV cash flow, which grows from \$0 to \$3 million over 20 years. This result confirms that the proposed interventions improve the RRP's overall NPV over the 20-year study period and that the model is a fiscally sound investment resulting in financial gain and improved road function. Moreover, using the NPV method, stakeholders can also compare the money invested with the future returns over time (Weber, 2014).

5.4.5 Policy Analyses

The authors of this study conducted counterfactual experiments to examine potential changes in the total costs (what-if scenarios), starting with a sensitivity analysis defining the policies and determining which is most effective. These results compare system behavior with the baseline scenario represented in Figure 5.3(a) in section 5.4.1 and Figure A III 1 for all five road qualities. Ultimately, three policies were defined, including: Policy 1 (P1) determining the optimal budget allocation and average time to rehabilitate; Policy 2 (P2) promoting maintenance over rehabilitation; and Policy 3 (P3) combining optimization and maintenance. All policies were tested for 20 years, demonstrating the short-term and long-term system responses.

5.4.5.1 Sensitivity analysis to define policies

This study used the following parameters to simulate different amounts of road damage: (1) age 1, initial road degradation; (2) age 2 to 3, structural fatigue; and (3) age 5 to 6, cracking disintegration. These three early road damage parameters allow stakeholders simulate the speed at which a road changes from one status to the next, so that funds can be invested appropriately to prevent it.

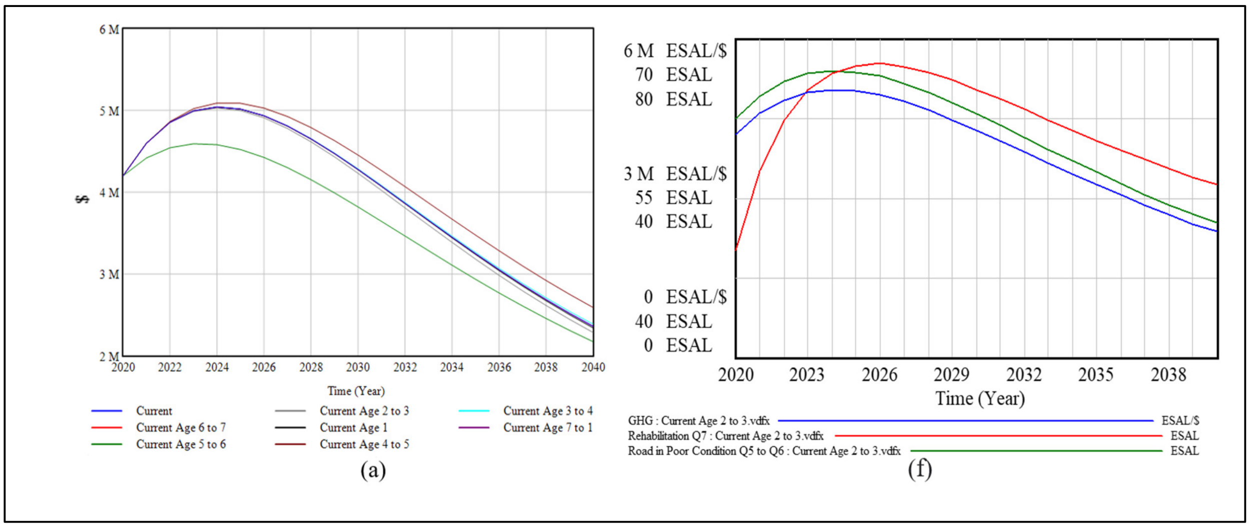

Figure 5-8 Total cost by age and GHG for roads in poor condition over time

Combining Figures 5.8(a) and (b) with Figures 5.5(a) to (c) show that the most effective policy to reduce costs (total and user) and emissions while increasing the APL is to increase the parameter Age 5 to 6, reducing spending on cracking and disintegration by 2040. Notably, Figure 5.5(c) shows that the riskiest policy is to not take care of the flow from poor condition to rehabilitation. This policy increases the total cost significantly, so the best strategy is to take care of the roads in poor condition and not delay rehabilitation.

5.4.5.2 Policy 1: Determining optimal budget allocation and average time to rehabilitate

P1 is determined by changing (1) the budget fraction from \$4 million (base-run value) to \$7 million and (2) the average time to rehabilitate. The analysis also included reductions from \$4 million to \$2 million (less than 50%) by the end of the simulation time. Figure 5.8(a) compares the base-run results for the five main outcome variables: very good, good, fair, and poor condition, as well as rehabilitation activities.

In each graph from Figures 5.8(a) and 5.5(a) to (c), the thick blue line represents the original base-run simulated behavior, which is assumed to be at 50%. The other thinner curves indicate the different simulations associated with P1. Changes are based on multiple budget allocations and occur after 2023 in some behaviors and from 2020 in others. For example, as the ESAL increases for roads in very good and good condition, so does the rehabilitation cost and the average time to rehabilitate. As the rate drops, so do the numbers.

Figures 5.8(a) and 5.5(a)-(c) illustrate that, although an HP budget allocation produces a rise of 60% over the first two years, a 50% ratio only attains a 10% improvement over the same period. This means that when keeping the road in very good and good condition is the top priority, system conditions improve at a significantly higher rate. As well, when rehabilitation spending is over $4 million, roads in very good and good condition increase while those in fair and poor condition decrease. The opposite is true when the spending is under $4 million, which is consistent with WSP report findings.

Overall, Figures 5.8(a) and 5.5(a)-(c) reveal that, although the system achieves similar outcomes by 2020 for different budget allocations, system behavior between 2020 and 2040 varies according to maintenance budget allocations. If stakeholders had wanted to keep the RR33 and other road sections in very good and good condition while also significantly decreasing short-term rehabilitation costs, it would have been necessary to raise the rehabilitation budget allocation from $4 million to over $7 million. Moreover, if the average time of rehabilitation is reduced by half, spending will shrink below $4 million by keeping up the very good and good condition roads over the long-term. This last scenario is the optimal solution because the roads are maintained in very good and good condition, and the long-term spending is the lowest.

5.4.5.3 Policy 2: Promoting maintenance over rehabilitation

The purpose of P2 was to identify the impacts of prioritizing maintenance over rehabilitation, encouraging time reduction and continuous maintenance of roadways in fair conditions. The time decreases were made to satisfy Tunisian stakeholder goals – the average time to fix roads parameter was cut by half, from 1 to 0.5, and increased by half, from 1 to 1.5 years. Figure 5.8(a) shows how P2 affects the outcomes scenarios from P1.

Results show that road network condition ameliorated when P2 was implemented. By 2040, roadways in good condition had grown by 60%, and those in fair condition had dropped by 35%. Finally, poor condition roadways had diminished by 20%. Therefore, increasing the rate of maintenance also entails early intervention, consequent higher initial costs and increased emitted GHG mid-simulation from 2030-2036 (see Figure 5.8[b] and 5.5[b]). Nevertheless, both emissions and costs will decrease by 2040. Although the cost savings are not exceptional, Figure 5.8(b) shows a uniform distribution of costs over time, showing no need for excessive early investments. Findings show that governments should focus their efforts and investments on maintaining fair condition roadways. This policy makes it possible for the network to shrink emissions and costs and keep the roads in superior service conditions for longer.

5.4.5.4 Policy 3: Combining P1 and P2

P3 was created to attain better results for the model components: physical environment, technical system, economic activities, and sustainable pavement solutions. For this goal, P1 and P2 were combined, simultaneously modifying the following parameters: road ages, costs of user's road in fait and poor conditions rehabilitation in sustainable way percentage, and average time to fix roadways.

Three sub-policies were tested: sub-policy 1 (P3-1) promotes sustainable maintenance practices; P3-2 promotes sustainable construction practices; and P3-3 combines the first two. The sub-policies' sustainable rehabilitation and construction percentages were adjusted to fall between the baseline of 50% and 100%, or the highest level of system benefits. Additionally, like in P1, the average time to fix roadways was decreased for all sub-policies from 1 to 1.5 and decreased from 1 to 0.5 years. Figure 5.8(a) compares the baseline and P3 sub-policies for the other analyzed outcomes. Since the network condition relies on the rehabilitation policy, the lengths of roadways in good, fair, and poor conditions are the same as in P2.

Overall, P3 shows that the highest reductions in costs and emissions will be realized by 2040. For P3-1, changing the maintenance rate cut down costs and emissions by roughly half. This relationship occurs because the GHG will decrease as the roads improve and vice versa. The emissions and costs decreased for P3-2, which encouraged sustainable construction activities. Finally, in the case of P3-3, which combines P3-1 and P3-2, emissions were cut by half. Ultimately, P3 shows how governments can achieve more significant sustainability by developing infrastructure policies that simultaneously assess various parameters.

5.4.6 Model testing and validation

Standard methods for SD were used to test the model, which is designed to reproduce the RRP network's actual conditions from 2020 to 2040. As explained above, the study assumed that the construction and rehabilitation activities were created using traditional pavement technical solutions. Partial model calibration procedures were used to calculate the road rehabilitation rates (Fallah-Fini et al. 2010; Guevara et al. 2017). Specifically, an assessment tool was used to identify the parameter combination able to produce the best fit concerning historical data. This process is widely used in SD literature, and it reduced the gap between the actual data and the simulation results.

To create the proposed model, formulations were used that have previously been employed in SD literature for assessing road networks. For example, aging chains were used that helped recreate the process of deterioration (Fallah-Fini *et al.*, 2015; Guevara *et al.*, 2017; Ruiz & Guevara, 2020; J. D. Sterman, 2000). To verify that the model behaved logically and ensure structural and dimensional consistency, a set of tests was also carried out. For instance, it was ensured that the model's stocks maintain positive values, irrespective of the exogenous parameters' values. Extreme condition and sensitivity tests (Sterman 2000) were conducted using Vensim PLE+ version 8.2.0, an SD modeling software, to evaluate system behavior under various conditions (Ventana 2021).

For all the simulations, the results demonstrate that each parameter behaved logically. Indeed, their mean values showed similar trends to studies described above that used historical data (Ruiz & Guevara, 2020; Guevara *et al.*, 2017; Fallah-Fini *et al.*, 2015). This trend comparison assessed four variables for roads in very good, good, fair, and poor condition. These variables describe the system's state, and their data is available to the public. The simulation results are shown in Figure 5.3(a) in section 5.4.1. Additionally, each service condition's distance is measured in kilometers-roadway and was obtained using data from a case study, signified by discrete data points.

The simulation satisfactorily reproduces the same trends as those observed in studies using historical data. A statistical test could be conducted to assess the model's ability to characterize historical data using indicators. Examples include the root mean square error (RMSE), Theil's inequalities, and the coefficient of determination (R^2) (Sterman, 2000; Guevara *et al.*, 2017). These represent how the mean square error (MSE) can be dispersed as three error types: unequal variation (US), unequal covariation (UC), and bias (UM). However, R^2 cannot present a value approximate to one, and Sterman (2000) argued that this is an unsuitable indicator for systems assessment. Instead, it is better to use RMSE, which penalizes significant errors and ignores small mistakes. Moreover, these low R^2 values are not surprising due to several influencing factors outside this study's scope. Table 5.3 summarizes the values estimated for these statistical metrics.

Table 5.3 Statistical tests' estimated values (2017, p.7)

Indicator	**Road condition**			
	Very good and good	Fair	Poor	Rehabilitation
R^2	0.94	0.86	0.945	0.484
RMSE	24 k	2.5×10^4	4.1×10^3	4.2×10^9
Bias (UM)	0.25	0.44	0.21	0.13

There is a good fit between the historical data and the model results despite the point-by-point differences. In addition, Table 5.3 also shows that in two road conditions (fair and poor), the majority of errors occur in the UC. For very good and good condition roads, the third variable has more UC than US, but the difference is insignificant. Sterman (2000) explained that when the UC is sizable, the model can identify the data’s trends and the mean. The dissimilarities are produced by the data’s random nature, meaning that most errors are unsystematic (Sterman, 2000). Thus, it can be deduced that the simulation has a good fit with the historical data, confirming that the model simulates the real-life system’s behavior.

5.5 Conclusion

The present work combined VPDAM and SD simulation to investigate climate change’s long-term impacts on pavement performance, rehabilitation activities, and sustainable CDW management. It then optimized the RRP’s rehabilitation practices at the project level to validate the proposed model. Ultimately, a framework was suggested for using SD to integrate pavement performance, sustainability, climate change, and pavement maintenance economics.

The findings suggest two important conclusions. First, the study showed that combining VPDAM and SD can provide a nuanced and sustainable pavement rehabilitation plan at the route level while considering the effects of climate change. Indeed, modeling, simulation, and optimization demonstrate that climate change has a significant long-term impact on pavement performance.

Second, results indicate that the expected climate change is likely to significantly reduce the road network’s extant subgrade and HMA stiffness properties. The HMA’s anticipated reduced stiffness will cause faster deterioration, drastically lowering the average pavement life. Thus, a sustainable reclaimed cement rigid pavement solution is recommended to ensure a longer average pavement life in the Mediterranean climate with the specific ESAL. Thus, the present paper demonstrates that over 20 years, environmental influences rooted in climate change are expected to significantly and erratically increase the RRP’s road rehabilitation costs. Studies that do not consider climate change and its effects on pavement performance do not account for the early and significant increase in rehabilitation costs.

5.5.1 Scope and limitations

Like all studies, many limitations to the present work impact its scope. For instance, lack of funds and stakeholder ignorance regarding SD may pose challenges to implementing the proposed model. Thus, stakeholders must be educated about SD, the benefits of reusing recycled CDW, and how to implement the model's policies. Indeed, one of the biggest challenges to improving road management in developing countries is convincing stakeholders to use recycled material for cost savings. As well, bringing together different departments concerned with road management, construction and rehabilitation is a challenge to modeling the relationships between the parameters affecting road performance (i.e., economic, technical, and climatic). Integrating social, administrative and economic consultation into the implementation process of the proposed model could help offset the above issues. These are mostly issues related to psychology and human resources administration. Future research could focus on SD implementation issues among non-academic stakeholders.

Another problem with SD validation is that the substantial interrelationships underlying the major variables make it challenging to thoroughly examine all the possible dynamic interactions using one model. Thus, only a few scenarios are provided in any given paper. Moreover, due to resource limitations, it was only possible to collect data from one real-world project for testing and validating the model. Finally, since the model was only run for twenty years, changes after 2040 remain unknown.

5.5.2 Novel contributions

The present work makes novel contributions to the literature on PMS, SD modeling, sustainable development, and engineering management. The first contribution to PMS literature is triangulated data and research methods, such as interviews, government data, policy analysis, SD, and the VPDAM. Triangulated data and methods increased the results' validity and reliability via cross-substantiation. The second contribution to PMS literature is combining SD with the VPDAM to identify the best sustainable road intervention strategies on technical, environmental, and economic grounds to allocate optimal road rehabilitation budgets on the network level.

The third contribution is SD model validation. The system was tested using a case study on the RRP's extension and projected rehabilitation roadworks. This validation is a novel contribution because it is the first time the RRP has been examined using both SD and the VPDAM. Moreover, no other studies have used existing data to predict the RRP's future. Ultimately, this paper developed three policies for optimizing rehabilitation budgets and promoting sustainability given a set of environmental and operational conditions. These policies were designed to ensure stakeholder participation and enable them to achieve a sustainable road maintenance system.

5.5.3 Research recommendations

This paper makes four recommendations for future research and validation of similar projects. The first is to gain more relevant and accurate climate change data in other regions. This data must be particular to the study regions, especially those in more vulnerable environments, such as coastal areas. Secondly, SD is recommended for testing more policy scenarios to investigate their impact on PMS. Other methods should also be utilized to verify the robustness of the projects, including agent-based modeling, multi-criteria analysis using the analytic hierarchy process, modeling using Ecorce 2.0 and HDM-4 tools, and sensitivity analyses. The third recommendation is to conduct site-specific modeling and simulations in other regions and climates to predict the variance in the climate change impacts on pavement performance, transportation networks, and associated economic factors. Finally, further research should be conducted in modeling accuracy and prediction refinement. This information will enhance modeling to mirror real-world situations by adjusting parameters based on data from other case studies. The proposed actions will enable stakeholders to better understand a route or network's future needs by identifying vulnerabilities and trends, helping them prepare research plans, develop appropriate road rehabilitation materials and methods, allocate budgets, and optimize tax dollar spending.

CONCLUSION

This dissertation investigates CDW management in developing countries, develops a framework and draws a methodology for its sustainable recycling. Developing countries suffer similarly from corruption and lack of CDW policy while having similar cultural and social norms. As well, developing countries lag considerably behind developed nations in terms of sustainable CDW management policy, which indicates that research in this area is urgently relevant.

The overarching research question of this study comes in two parts:

- What is the best reason, method and time to intervene in the CDW life cycle?
- What policymaker/stakeholder decisions best address sustainable CDW management needs?

Three main studies make up the structure of this dissertation. Chapter 3 sets out to identify tools and methods for estimating the amount and assessing the type of CDW created and illegally dumped in developing nations in North Africa and the Middle East. An SD model is developed using specific variables and parameters to carry out this assessment. A significant parameter for CDW characterization is cement consumption and production, since it helps identify and estimate the materials being used in the construction sector whether or not they can be recycled or reused. Additional parameters include GDP and population growth. The SD process quantifies these variables and weighs them for their significance and value. Because no tools exist in the Libyan context for assessing CDW, the resulting SD model is the first method to approximate the in- and outflow of CD materials being used in the country. The findings of this study demonstrate that Libyan manufacture and importation needs are high, necessitating similarly high use of CD materials which inevitably leads to high CDW. As well, the 2011-2019 conflict has produced a lot of CDW. Consequently, a recycling program is urgently needed to address the CDW accumulation in Libyan landfills and illegal dumping sites.

The overall objective of Chapter 4 was to address the institutional barriers to recycling and incentivize construction project stakeholders and decision-makers to recycle CDW. By replacing conventional methods like increasing fees and fines for illegal waste dumping, the study sought to promote cooperation between the government and contractors such that recycling became a cost-saving measure that is attractive to contractors and not prone to abuse or corruption. The initial step (1) of the solution strategy an SD model based on CLD and SFD.

These diagrams showed the interrelationships between the main parameters affecting CDW management in the region being studied. The result was an SD model capable of predicting the future CDW conditions and the relative efficiency of a recycling initiative before its implementation. The subsequent step (2) of the recycling strategy was the design of a virgin-for-used-material exchange (V4UX) program as part of a case study in Nalut, Libya, in consultation with project and government stakeholders. Contractors working to rehabilitate Almarabeh Road were advised to bring used materials to a recycling centre in exchange for new materials with the promise that the resulting recycled material would be subsequently sold at a lower cost. This demonstrated considerable savings to stakeholders and simultaneously limited the possibility of the mismanagement of funds, benefitted the environment and dissuaded illegal dumping. The simulated V4UX program was successful at motivating stakeholders to bring back their used CDW in exchange for reused untreated asphalt which they were then able to use effectively on unpaved farm roads. Using asphalt successfully on unpaved roads convinced the contractors that it could be used for building other, higher-traffic roads. This validated the SD model based on the V4UX program and demonstrated that cost-saving incentives are a strong motivator for Libyan contractors.

Chapter 5 integrates several significant pillars of sustainability (environmental, economic, and technical) in a sustainable solution to the problem of pavement management systems. As well, part of the objective was to validate the previously developed SD model further in a new case study in RRP, Tunisia. A set of parameters affecting pavement rehabilitation was used in the SD model according to the above sustainability criteria. The physical environment parameter considered the effects of climate change and greenhouse gas emissions on road conditions; the economic activity parameter considered average pavement life and budget availability/deficits; the technical systems parameter considered pavement deterioration levels, road treatment delays and Equivalent Single Axle Load (ESAL); and the sustainable pavement solutions parameter considered the number of required sustainable solutions and type of rehabilitation activities.

The SD model was combined with the VPDAM to assess the type of effects on road conditions while predicting road performance over the next 20 years. A case study of the RRP used recycled construction materials for pavement rehabilitation (e.g., backfilling of potholes), which had significant environmental benefits as compared to using new materials.

According to the study's findings, the road's lesser current and estimated traffic volumes can reduce the asphalt layer's thickness for both alternative flexible pavements, resulting in significant cost savings. Additionally, the SD and VPDAM methods was combined to predict the optimal materials and construction conditions for increased pavement longevity. Finally, the best time to invest in pavement rehabilitation given all other situational parameters was determined using the NPV metric.

This study found that it is possible to estimate and characterize CDW by analyzing cement production and consumption and integrating these with GDP and population growth indicators. A System Dynamics model was built to assess the factors impacting CDW management performance and help stakeholders manage waste in efficient ways. A V4UX program was developed to manage illegal dumping of CDW and conserve raw materials. Subsequently, a technical parameter was added to the established sustainability definition including environmental, social and economic pillars, in the interests of adhering to several goals from the 2030 UN Agenda for Sustainable Development. The management policy scenario analysis for improving CDW was carried out both for present scenarios and possible future scenarios using the SD model. Two case studies are carried out to validate the use of SD in the CDW management sector, namely:

- Libyan CDW was characterized (SD and VPDAM) and an intervention strategy was developed for its more sustainable management (V4UX) for 2 km of road undergoing rehabilitation, taking into account stakeholder motivation and the likelihood of implementation.
- An intervention strategy for reusing CDW to rehabilitate eight sections of a road network in Tunisian Rades Road Port, assessing the main road section rehabilitation results (system dynamics and VIZIR Pavement Distress Assessment Method).

RESEARCH CONTRIBUTIONS

Each of the studies comprising this dissertation has a unique contribution to make to the fields of CDW management and environmental engineering and their methodologies. In existing literature there are many mathematical methods that can estimate CDW. However, as seen in Chapter 1, systematic use of new parameters such as cement production and consumption along with economic factors yields a much more precise estimate.

This is also a new way of estimating CDW in Libya specifically, since computer-based modelling that includes variables specific to the area being studied is a more accurate measure of CDW type and quantity. As well, the SDM method is relatively easy to use – the parameters are integrated in a simple, quick and cost-effective way.

Using SD helps recognize new parameters and account for new problems, uncertainties, and unforeseen situations. For example, Libya used to be an economically stable country with a regular inflow and outflow of materials. However, the 2011-2019 conflict has greatly increased CDW. SD is much more effective at assessing current issues and predicting future problems and outcomes because its parameters can be changed according to what becomes relevant in any given time.

Chapter 4 explores the use of V4UX to incentivize construction project stakeholders to recycle CDW. The methodological novelty of this study is the CLD that was developed as part of the SDM, once again considering location-specific parameters and making it possible to predict future performance of hypothetical recycling programs. An additional research contribution made in Chapter 4 is the use of psychological principles of motivation in the field of CDW management. Existing studies for motivating behavior in the construction sector involve punishment measures and often neglect to account for existing stakeholders, are non-context specific, and usually carried out in developed or economically stable countries making them easy to implement. Here, taxes, fines, fees, and various other punishment measures are referred to as traditional methods of motivation. Ultimately, the V4UX program was found to be effective in developing countries like Libya, where policy and law is less evenly applied and easier to evade.

This study uses positive motivation (the carrot) instead of negative motivation (the stick), which is generally likelier to produce the expected behavior as established in psychological studies. Additionally, this study shows that, in the developing context, abuse of resources is minimized through indirect positive motivation (cost savings) instead of direct motivation (funds). This results in synergy between contractors and government officials, allowing both to benefit greatly from the recycling of CDW through cost-saving measures and decreased illegal dumping, respectively. Overall, the results show that the V4UX results in greater environmental and social sustainability.

The final study, found in Chapter 5 also makes methodological and practical research contributions. Based on the 2030 UN Agenda for Sustainable Development and recommendations from the Austrian Academy of Sciences, the study proposes an additional "technical" pillar of sustainability for construction and demolition projects. This road rehabilitation case study demonstrates that sustainability principles must be integrated into technical design from the outset of the project in order to produce truly sustainable results.

In the case of the RRP, the intervention carried out by the MCC was sustainable from the very beginning, in that the CDW meant for road rehabilitation was gathered from the ocean and minimal VM was used. Moreover, the community benefitted socially from the project (e.g., increased job creation and reduced illegally dumped waste).

The methodological novelty of this study is the combination of VPDAM and SD, which constructs a framework for the assessment of current road conditions and prediction of future performance and deterioration. This framework is accessible for use by government officials, transportation administrators, contractors, and anyone else who seeks to design a construction or rehabilitation project and predict its costs, sustainability, performance, and overall technical requirements.

The global contribution of this dissertation is an adaptable framework for sustainable CDW management in developing countries like Libya, although, sustainable initiatives preserving a local environment also play a part in protecting the global environment. Technical solutions for the management of existing construction and demolition waste or rehabilitation of damaged roads can be globally relevant as well. Most current research on CDW management lay the groundwork for this type of framework. This study builds a substantive and validated computer-based model that considers both the sustainability and implement ability of a project alongside its technical variables.

There is a social context to all engineering solutions. This study provides the tools and steps required to consider the technical, environmental, economic and social aspects of CDW management. As well, the research suggests program design solutions that would successfully motivate stakeholders to manage CDW in a sustainable way according to globally recognized sustainability standards.

STUDY LIMITATIONS

Integrating parameters from different fields is challenging. In the case of qualitative social parameters, it can be difficult to assign them a quantitative value such that they might be weighed accurately against other inherently quantitative monetizing parameters. Errors in the values assigned to qualitative parameters can create some level of uncertainty in predicted scenarios.

Further case studies are required for more rigorous validation of the proposed models using the same parameters specific to each location. This dissertation proposes three SD models with different parameters, and the first is validated using general literature review data on CDW characteristics and quantities. Unlike the other two studies, the first is not validated using a specific case study involving a practical intervention. As well, re-testing the remaining models with further case studies is needed to attain more accurate results. Finally, adjusting existing models by adding new parameters would yield more useful and accurate results.

Studies used a version of SD modelling software which does not have enough mathematical tools for further scenario analysis. For example, NPV was calculated by trial and error because the version used by the researcher did not support the automatic calculation of NPV. A more advanced version of SD modelling software would support a greater number of parameters to automatically analyze a greater number of possible scenarios.

RECOMMENDATIONS

The initial SD model characterizing and quantifying Libyan CDW was based entirely on secondary sources included in the literature review. It is recommended that a specific case study be conducted for further validation.

The study involving V4UX and recycling incentives resulted in the application of recycled CDW on parts of rural farm roads as a test of material quality. Since the test was successful and contractors were satisfied with the results, it is recommended that further studies are conducted on the reuse of demolished materials.

The benefits of recycling and reuse of CDW should be widely publicized among construction sector stakeholders to encourage the adoption of this sustainable practice and combat the belief that waste materials are of lower quality and use value.

Given that the interventions discussed in this dissertation were applied to relatively short test sections of roads, it is recommended that longer road sections under various conditions and external pressures be used to further validate the sustainability strategy in applying CDW in road rehabilitation projects.

The VIZIR method was used to compare three forms of physical road deterioration. It is recommended that future studies include a greater number of deterioration variables for a more detailed analysis. Studies including social parameters of sustainability are also recommended, since the focus of CDW management studies is often limited to a combination of economic and environmental factors only. Metrics for the social pillar of sustainability are what ultimately demonstrates how well practical projects will serve the populations for whom they are built, and whether or not their social effect will be positive or negative.

The ultimate expected benefits and industrial impacts of this thesis, financially supported by a grant from the MENA stakeholders (e.g. Libyan and Tunisian Governments), are to recommend wider application of this model across Libya and Tunisia. This broader user would: (1) mitigate the consumption of new materials and make it financially viable or even profitable to use recycled material, (2) reduce the use and creation of landfills by reclaiming materials and instituting a higher cost for new landfills, (3) reduce the transportation of materials by using an appropriate management system that can inform users of available materials closer and at a lower cost, (4) reduce greenhouse gas emissions, (5) reduce construction and maintenance costs, (6) raise productivity and save time, and finally, (7) improve the countries' quality of life and the local economy.

ANNEX I

Development of a Recycling System Policy for Construction and Demolition Waste Materials with Applications in Libya towards Sustainable Development

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Abstract

Construction and Demolition Waste (CDW) materials are presently put in landfills (henceforth, Landfill-Designated Waste). At the same time, many developing countries, particularly in Africa, suffer from a lack of proper management of suitable materials for road construction, mainly old concrete, brick, asphalt, gravel, and angular sand. CDW is significant because it may be fully or at least partially reused in new construction projects, saving valuable and non-renewable resources. In addition to the depletion of natural resources, the disposal of CDW causes clogging of disposal sites. Due to the absence of a recycling and reusing policy, there are no alternatives to these disposal sites where CDW piles up. The three challenges to recycling are: 1) landfill space which is cheap or free; 2) social norms and education surrounding recycling; and 3) waste is perceived as garbage, and therefore of lesser quality. By quantifying how landfilling CDW represents an increase in environmental liability and a problem for the future, this research discusses the waste of the potential value of the material and how existing and scarce resources might be protected. Thus, CDW is a liability that can be turned into a valuable resource by using System Dynamics (SD) concepts. In addition, SD presents a convenient framework to monetize the value of the recycled waste. This framework is based by characterizing CDW and then on reusing it. The results of the model provide an

innovative needs-based recycling policy to manage CDW. The scope of the study is at the national level, focused on Libya but generalizable to developing countries with comparable climatic, social and cultural features. Validation in this study relies on three things: 1) verifying that the units that are input into the model are correct; 2) comparing the results with successful previous studies; 3) using one specific and very common building design. This needs-based approach regarding required construction materials relies on estimates of future material needs, from either new or recycled sources, for both new and rehabilitation projects.

This assessment is based on infrastructure needs, population growth rates, GDP, and cement production and consumption

Keywords:

Recycling; Construction and demolition Waste Material; System dynamics; Modelling; Cement consumption; Cement production; Road construction; Environmental, Sustainability; Libya.

Specific Issues

The construction of new projects, renovation, and demolition wastes from infrastructure development can have a great impact on the environment, and on energy and material consumption if they are not regulated(Marzouk & Azab, 2014)

The general unwillingness to accept second-hand or recycled materials creates a lower demand for recovered or recycled materials on the market. Nonetheless, the end goal of the project is to develop a sustainable model of waste management that is appropriate to the social and physical environment as wellas to the economy of a country such as Libya. The recycling of materials helps to reduce landfill pressures.

During the design stage of construction projects, sustainability principles for holistically integrating material selection must be incorporated. There is a lot of research in this area but there are still many obstacles to incorporating sustainability concerns in material selection in order to make the appropriate decision.

Objectives to Establishing a Sustainable Framework Research

The main goal of this study is to devise a framework and methodology for a developing nation to establish a recycling policy for construction materials from a socially, economically and environmentally sustainable perspective.

The specific objectives of this research are:

1) Identify and characterize existing CDW at the national and city levels in a developing country such as Libya; these must comply with relevant and generally accepted guidelines and standards in order to establish a reliable and dependable accounting of potential material assets for different reuse needs.
2) Propose an adapted recycling policy framework for Libya and similar developing countries. (Nazirah Zainul Abidin (2010) defines sustainable construction as an approach towards the future in which the needs of development are balanced with a duty to protect the natural environment, public health, and economic security; i.e., the goal is to develop places that are prosperous for public and environmental health, and work.

Methodology

The application of SD in this study relies on the VENSIM PLE software. This program has a graphicaluser interface (GUI) that is useful to help the user design and test a system dynamics model. The model aims to reproduce the Reference Behaviour Patterns (RBP) of the roadwork construction sector as it pertains to buildings that will be reused, recovered, and recycled into base and subbase materials for road construction. Once these are properly defined, it will be possible to consider how policies and community behavior affect the goal of using recycling to move towards zero landfill waste.

What distinguishes this research is that it introduces the modelling of cement production and consumptionvalues pertaining to buildings. (Ali *et al.*, 2016) points out that cement is crucial to making concrete and that over 97% of Libyan construction employs cement (Ngab, 2007). For this reason, the first step is to use a statistical analysis of cement production to make an estimate of concrete in Libyan CDW. In other words, it can be easily determined how much cement is produced in or imported into the country; it can also be determined how much of this goes into construction in the country; because this holds true for the other construction materials, the composition of the CDW can be derived. Such an analysis is possible because there are good records of data pertaining to cement use, but it is also necessary to use such an analysis because fieldwork, that might otherwise be conducted, is not possible due to the political situation in Libya; there is also a general lack of consistent data on the kind and quantity of constructionprojects. Another way to qualify the data is by using a per capita comparison with countries that have similar social and economic characteristics, i.e. ones that derive their primary economic strength from petroleum exports and that have a similar cultural makeup.

Using Cement Consumption to Estimate Libyan CDW

In the 1970s, Libya was considered the highest per capita consumer of cement, averaging about six million tons each year (Ngab, 2007). From 1992 through 2006, the consumption of cement went up markedly from about four million tons per year to about seven million tons per year; this was because of alarge number of government construction projects. Prior to 2011, the government had initiated some projects to increase domestic cement production, aiming at bringing it up to about 13.5 million tons by 2010 (AUCBM, 2007); Libya was in fact producing about ten million tons annually. Libya does not produce enough cement to fulfill its own needs and therefore has imported much of this cement from neighboring countries, such as Egypt, Tunisia, and Turkey (Ali *et al.*, 2016). There had been plans to raise the levels of cement production to as much as 15 million tons before 2011; in fact, the Libyan government had issued permits to several foreign corporations to help make up the shortfall in cement production.

Table-A I-1 Construction developments in process or planned until 2010 (2016, p.844)

Company	*Project type*	*Type of cement*	*Planned production capacity under study**	*Planned production capacity under construction**	*Production started*
Libyan cement Fattaih Factory	A new production line	White	190	-	2008
Libyan cement Fattaih Factory	A new production line	White	-	-	2008
Libyan cement Fattaih Factory	A new production line	Normal	950	-	2008
Libyan cement Hawari Factory	A new production line	Normal	1330	-	2008
Libyan cement Benghazi Factory	Improving production line	Normal	475	-	2008
Ahlia Cement Factory Zliten	A new production line	Normal	-	900	2008
Ahlia Cement Factory Libdeh	A new production line	Normal	-	1500	2008
Ahlia Cement Factory Koms	A new production line	Normal	-	1500	2008
Orascom Group	New factory	Normal	-	-	2008
Total (8 projects)			**2945**	**3900**	
Total of expansions: 6845 *Thousands of tonnes per year					

Simulation and Policy

The Average GDP growth Rate and Fraction of GDP Going to Cement Production are critical factors in waste generation as shown in Figure 3.0. The results are shown in Figure 3.1, expressed as the following equation:

$$t = \text{Present production of concrete waste} \times (1+\Delta\ \text{GDP}) * (1+\Delta\ \text{Population}) \qquad \text{(A I-1)}$$

Where: = future production of concrete waste

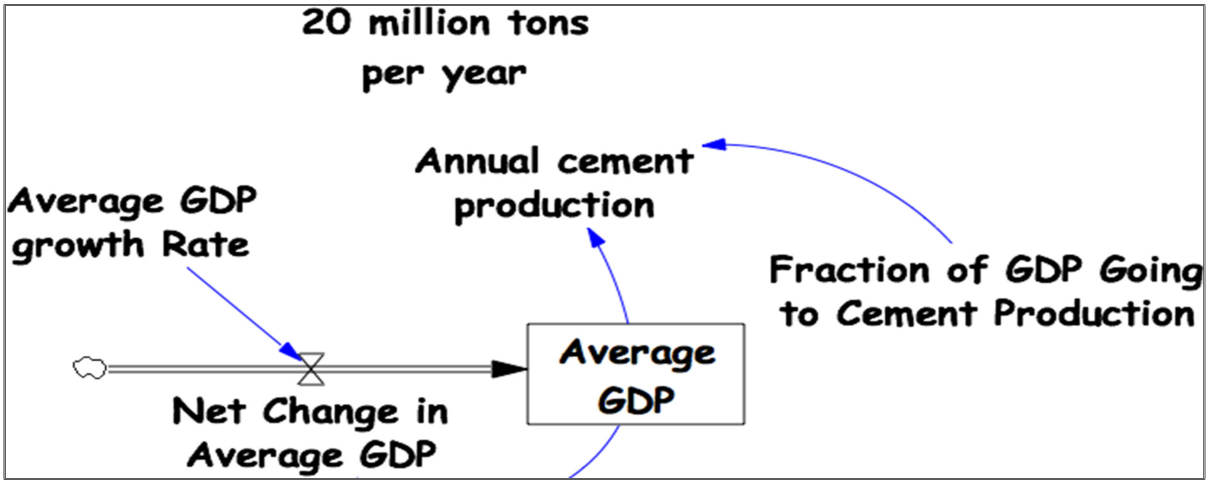

Figure-A I- 1 SFD for Average GDP and the Net Change in the Average GDP

effects the Annual cement production

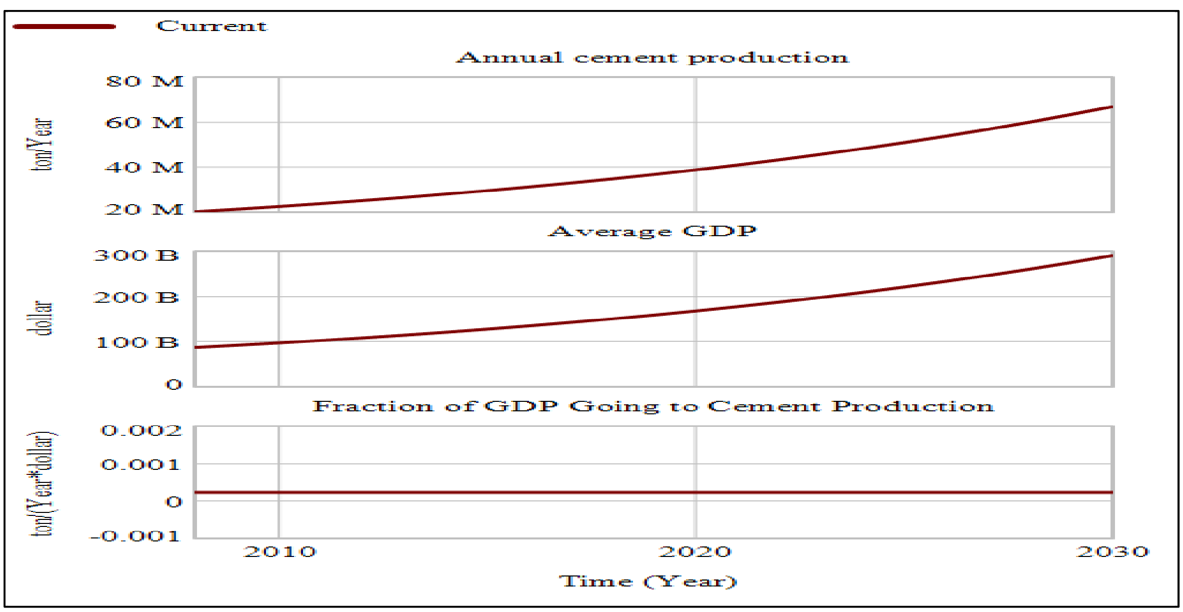

Figure-A I- 2 Output of the scenarios between Annual Cement Production,

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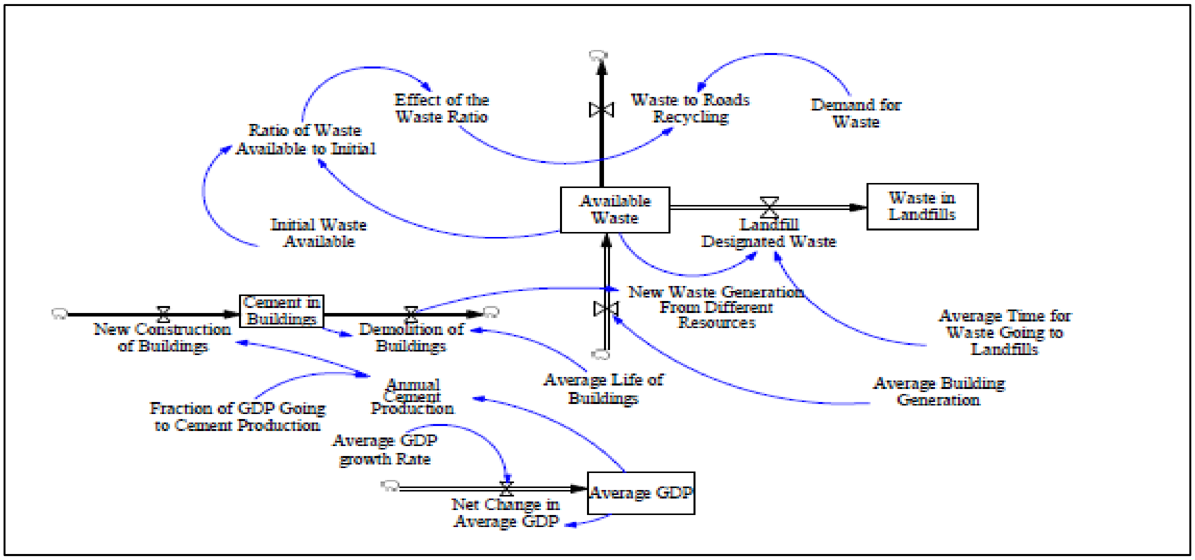

Figure-A I- 3 Model Benchmark for CDW Management and the Flows and Stocks

The data will be aggregated so that the model remains usable. As such, all recyclable materials will be counted together; the population and degree of urban development will determine the total user base; for the purposes of the model, this user base is assumed to be as active as possible given the facilities available. If such aggregation affects the results of the model, it is hoped that it is minimal and that the trade-off is reasonable, considering the scope of the project

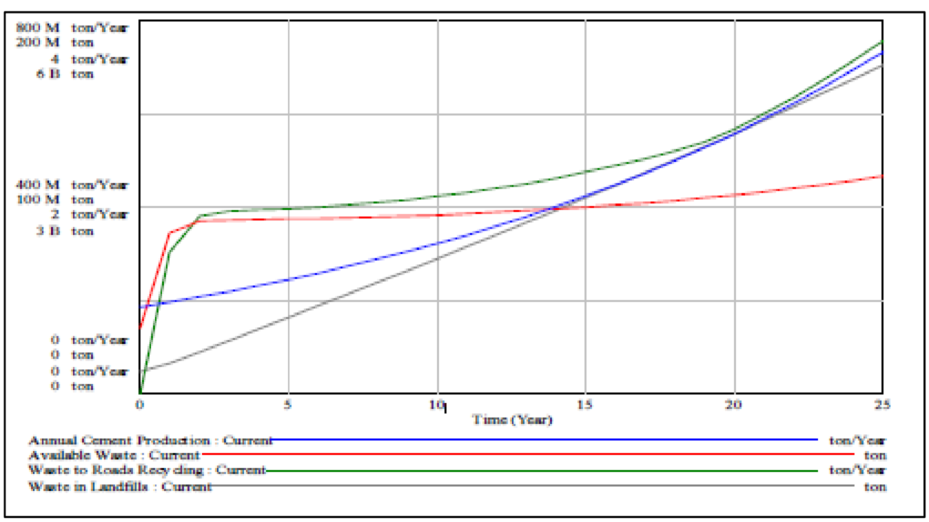

Figure-A I- 4 Landfill Waste, Annual Cement Production, and Waste to Road Recycling

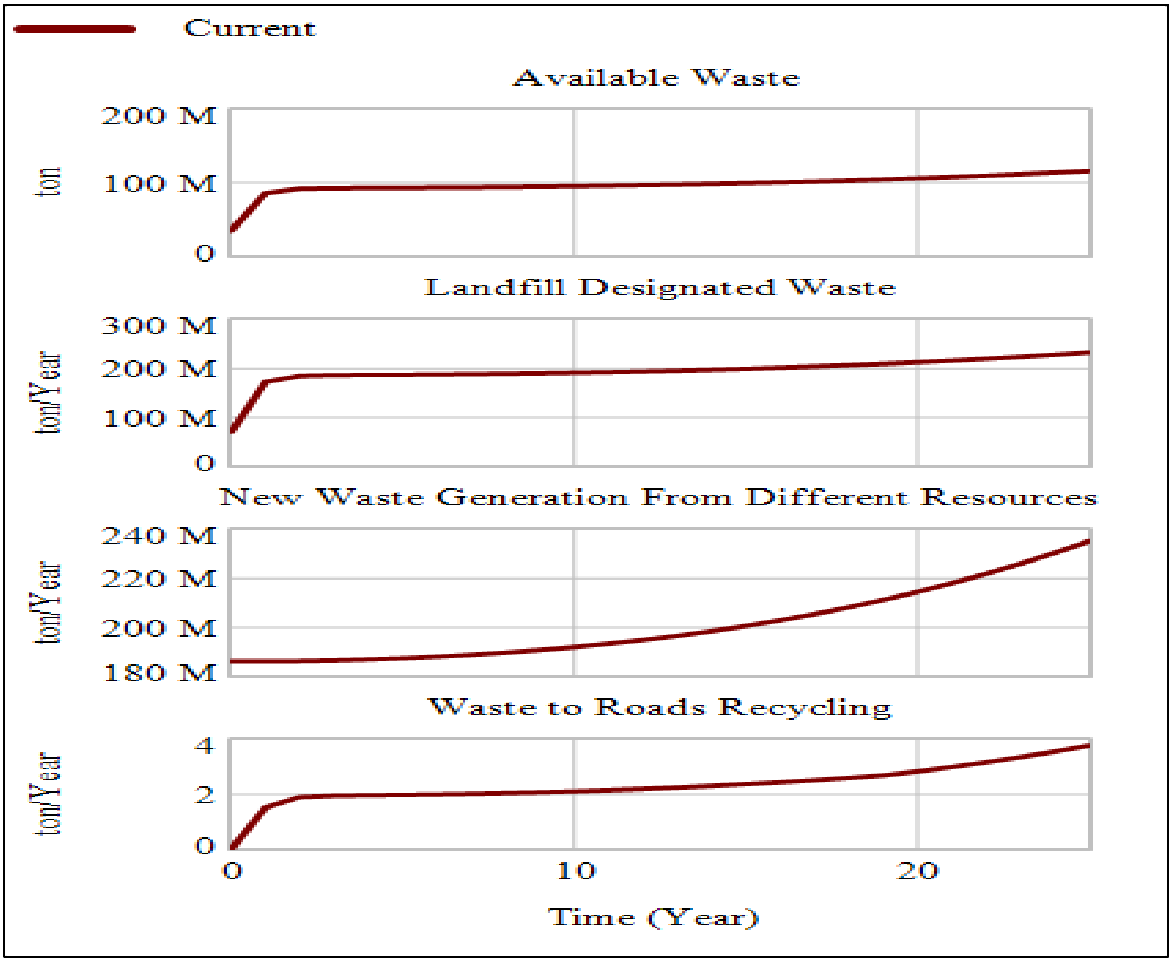

Figure-A I- 5 Available, Landfill, New Generation Wastes to Recycling

Validation and Verification

Validation and verification get easier as the model develops because these factors build on each other. These can be summarized into three categories, each of which includes highlights of the validation effortsthat were conducted. Validation in this study relies on three things: 1) verifying that the units that are input into the model are correct; 2) comparing the results with successful previous studies, for example (Bala, 2017; Mashayekhi, 1993), 3) Using one specific building, the specifications of which are discussed below. The present study successfully executed the first two validation steps.

Conclusion

The general trend is that, as the income of a community grows, this leads to the increase in building projects, and CDW. Around the world, there are a number of different methods of disposal; the most common are landfilling and open dumping. Landfilling is very common in industrialize countries butopen dumping is the most common in countries like Libya because there is little to no cost associatedwith it and it usually does not have any governmental organization. In this case, the outskirts of urban areas and natural geographic areas such as valleys are used for this. If recycling is ever to be economically attractive for many small governments, there must be a recovery phase, wherein useful materials can be extracted, and subsequently used in the base and subbase for future roadwork construction.

Figure 3.3 shows the results of the model illustrating how the Landfill-Designated Waste increases steadily over time. The behavior of the Annual Cement Production shows the same results; this is an important indication and implies that there is a significant relationship between Annual Cement Production and Landfill-Designated Waste. This will help the stakeholders make a suitable strategic planfor recycling CDW. As shown in figure 3.1, in 2005, the first year shown in the simulation, Libya had anannual cement production of about two million tons; in the same year, it had an annual GDP of US$100 billion; because the GDP growth is related to population growth, with a population estimate for 2030 of about 7 million people, the GDP is about. The construction sector in cities is tied to the grown rate of the GDP; the migration of populations into cities also stimulates construction. The outcome of more construction is the use of more cement, and the production of more waste. Therefore, more wastemanagement infrastructure is needed. Without recycling and reusing waste, there are two primary environmental effects: a scarcity of natural resources; landfill sites being clogged.

There is a growing crisis in Libya with regard to CDW because many cities are affected. This is a particular problem because there is a lot of CDW that still has not been collected from the 2011 revolution. There has also been a lot of economic growth since then (especially in 2012), and this inevitably leads to more CDW. This problem is not only a problem for Libya but also for similar countries, such as Syria and Iraq. The present model can be used to help solve this problem, and includes aspects such as Life-Cycle Cost Analysis (LCCA).

ANNEX II

Model Equations for Chapter (4) S (1-60)

1. Adapt coefficient of cost waste recycling= 0.5 Units: $*$/Month
2. Added VM percent= 0.0001 Units: km/$*1/Month
3. Amount of illegally dumped waste= New road rehabilitation project/Waste created per km Units: km/Month
4. Average cost of rehabilitation per km without V4UX= Rehabilitation cost per km with V4UX*Road rehabilitation in progress/25 Units: $*km
5. Average cost per km with V4UX= Rehabilitation cost per km without V4UX*Start of rehabilitation/5 Units: $*km
6. Average road life= 5 Units: Month
7. Circular economy= 1 Units: Dmnl
8. Cleaner environment= Improved local trade Units: $
9. Collection rate= 0.05 Units: 1/Month
10. Completing = Road rehabilitation in progress/Time to rehabilitate the road Units: km/Month
11. Cost of waste recycling= 5 Units: $
12. Cycles degrade by the rate= 10000 Units: Dmnl
13. Demolishing = Road completed/Average road life Units: km/Month
14. Downcycling= 10 Units: 1
15. Driving factors for waste recycling= Cleaner environment*RDW Units: $*Month
16. Dumping with V4UX= 750 Units: $/Ton
17. Dumping without V4UX= 0.75 Units: Dmnl
18. Economic efficiency with less corruption= 75 Units: Dmnl
19. FINAL TIME = 36 Units: Month The final time for the simulation.
20. Gap in road = KM required for entire road-Road completed Units: km
21. Illegal dumping with V4UX= V4UX*Added VM percent Units: km/Month

22. Illegal dumping without V4UX= New road rehabilitation project*Collection rate Units: km/Month
23. Improved international trade= Improved regulations Units: $
24. Improved local trade= Improved international trade*Economic efficiency with less corruption Units: $
25. Improved regulations= 0.5 Units: $
26. Improving level of RDW legislation= 0.025 Units: 1/Month
27. Indirect tax collection mechanism = 2000 Units: $/Ton
28. INITIAL TIME = 0 Units: Month The initial time for the simulation.
29. KM required for entire road= 8+STEP (1,10) Units: km
30. Material sold back= 1000 Units: $/Month
31. New road rehabilitation project= INTEG (Amount of illegally dumped waste + Illegal dumping without V4UX+Illegal dumping with V4UX +RDW increasing, 100) Units: km
32. Ongoing infrastructure investment costs= Rate of service allowance compensation*Recycling activities Units: $/Month
33. Planning= GAME (MAX (0, Replacement road + (Gap in road / Time to respond to the gap))) Units: km/Month
34. Rate of illegally dumped waste= Downcycling Units: 1
35. Rate of RDW= Cycles degrade by the rate*Demolishing Units: km/Month
36. Rate of service allowance compensation= 0.05 Units: $*$/Month
37. RDW = GAME (0.05) Units: Month
38. RDW increasing= Rate of RDW/Road waste per km Lookup Units: km/Month
39. Recycled material= Improving level of RDW legislation*V4UX/Traditional Gov funding Units: $/Month
40. Recycling activities= INTEG (Virgin material-Return of used recyclables + Ongoing infrastructure investment costs, 3500) Units: $
41. Rehabilitating= Start of rehabilitation/Time to plan rehabilitation Units: km/Month
42. Rehabilitation cost per km with V4UX= 45050 Units: $
43. Rehabilitation cost per km without V4UX= 2500 Units: $

44. Replacement road = Demolishing Units: km/Month
45. Return of used recyclables= Adapt coefficient of cost waste recycling/Recycling activities Units: $/Month
46. Road completed= INTEG (Completing-Demolishing, 2) Units: km
47. Road rehabilitation in progress= INTEG (Rehabilitating-Completing, Rehabilitating) Units: km
48. Road waste per km Lookup= ACTIVE INITIAL (Rate of illegally dumped waste, 0.5) Units: 1
49. SAVEPER = TIME STEP Units: Month [0,?] The frequency with which output is stored.
50. Start of rehabilitation= INTEG (Planning-Rehabilitating, Planning) Units: km
51. TIME STEP = 1 Units: Month [0,?] The time step for the simulation.
52. Time to plan rehabilitation= 2 Units: Month
53. Time to rehabilitate the road= 24 Units: Month
54. Time to respond to the gap= 2 Units: Month
55. Total cost=Average cost of rehabilitation per km without V4UX+Average cost per km with V4UX Units: $*km
56. Total virgin and recycled materials= IF THEN ELSE (Dumping with V4UX>0, Circular economy, Dumping without V4UX=0)/RDW + Indirect tax collection mechanism Units: $/(Month*Ton)
57. Traditional Gov funding= 1 Units: Dmnl
58. V4UX= INTEG (Recycled Material-Virgin material, 25000) Units: $
59. Virgin material = Cost of waste recycling/V4UX*Material sold back Units: $/Month
60. Waste created per km= 35 Units: Month

Supplemental Data for Figures:

For Type-B damage, rehabilitation begins after the visual identification of road damage, and no additional considerations are necessary to diagnose this damage type. Centerline cracking, for instance, requires crack-bridging while lacy edges indicate that the road's shoulders and edges need reconstruction. Conversely, the approach for Type-A damage identification depends on additional factors such as bearing capacity and traffic. Therefore, a general rating system of visible road conditions similar to the classes and rating systems utilized for the other factors is needed.

Significant rehabilitation is required to address Type-A damage (e.g., overlaying and rebuilding a road's surface layer). In contrast, Type-B damage results in maintenance and only affects the choice of treatment procedures when no Type-A damage is present. For instance, centerline crack-bridging to inhibit water permeation is futile without applying a wearing course on the road's surface. Indeed, the global visual index I_s, used for pavement condition assessment, only applies to Type-A damage.

The Roads Development Agency and Ghibaudo [1-2] describe three damage groups used to calculate the global visual index I_s, including (1) rutting and warping, (2) crazing and cracking, and (3) restorations. The I_s index ranges from 1 to 7 and is broken down into three road condition severity levels. Ratings of 1 and 2 indicate "good" surface conditions needing either no work or work that can be delayed without significant short-term harm. Road conditions meriting ratings 3 and 4 are deemed "intermediate" severity. They require roadwork maintenance without considering other intervening factors (e.g., lack of funding). Ratings of 5, 6, and 7 signify "very poor" visible road conditions necessitating significant maintenance or rehabilitation work.

Furthermore, Qi is a road quality rating metric approximated based on the combined values of the Is index (see Fig. A-II-1). As described above, the index assesses the visual conditions of road subgrade support and structure. Grounded in Qi ratings, the VIZIR method stipulates three levels of road maintenance and rehabilitation options. Ratings of Q1 to Q3 signify that no significant rehabilitation is needed. Roads that gain these ratings require routine and/or periodic maintenance. Given that these road sections show both types of damage, the present work prioritizes Type-A damage and remedies Type-B damage in passing. Similar to Mallick et al. [4] the present paper uses the term "rehabilitation" to include both rehabilitation and maintenance road work.

Ratings of Q4 to Q6 denote indeterminate and inconsistent visual inspection and deflection results. ANNEX III provides a process for reassessing a road's rating to reclassify it either as Q7-Q8 or Q2-Q3. Ratings of Q7 to Q9 indicate that rehabilitation such as structural overlay is needed. For further detail on how this paper uses Qi ratings in SD, see Fig. A-III-1 in the SFD section. This figure presents the ratings as stocks and demonstrates how they affect each other.

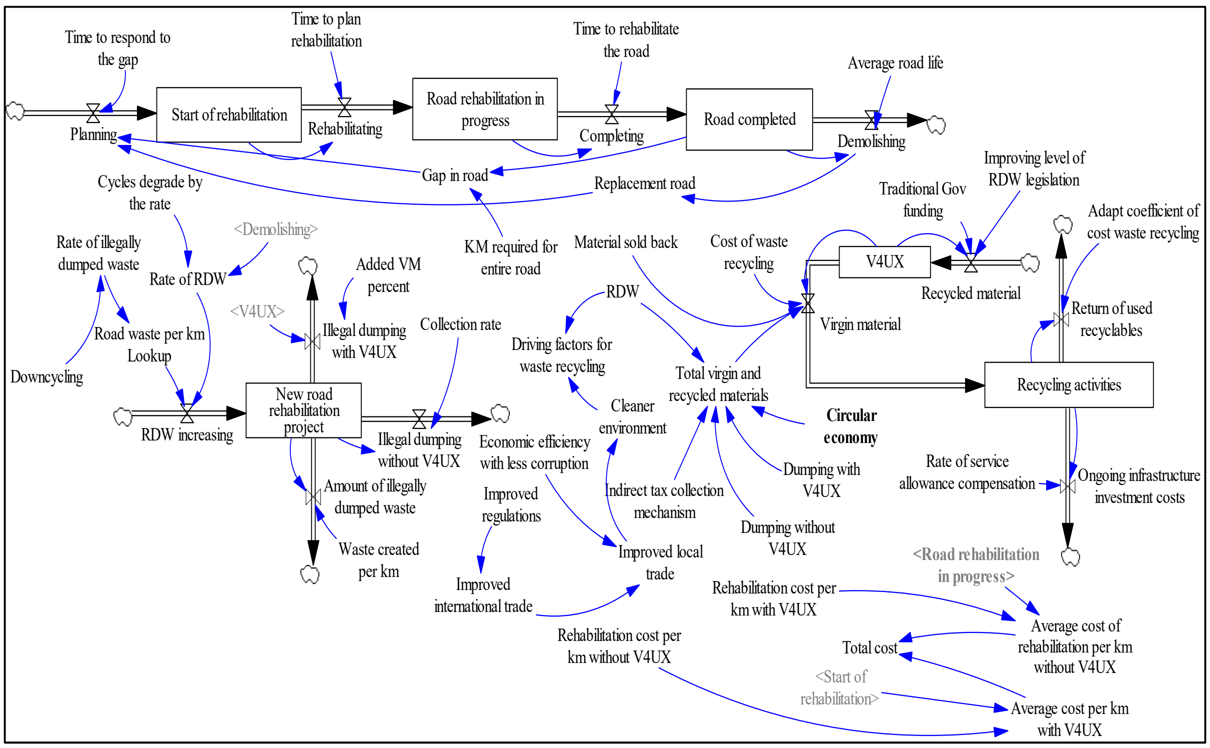

Figure-A II- 1 Complete stock-flow diagram for the V4UX proposal

ANNEX III

Description of the Types of Damage Described by VPDAM

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Given that these road sections show both types of damage, the present work prioritizes Type-A damage and remedies Type-B damage in passing. Similar to Mallick et al. (2014), the present paper uses the term “rehabilitation” to include both rehabilitation and maintenance road work.

***or alternative rehabilitation technique**

Deflection / Surface damage index Is	d1	d2	
	Class 1	Class 2	Class 3
1 - 2 Little or no cracking or no deformation	Q1 (maintenance)	Q3 (maintenance)	Q6 (to be reclassified)
3 - 4 Cracks with little or no deformation, deformation without cracks	Q2 (maintenance)	Q5 (to be reclassified)	Q8 (overlay)*
5 - 6 - 7 Cracks and deformation	Q4 (to be reclassified)	Q7 (overlay)*	Q9 (overlay)*

Figure- A III- 1 VPDAM quality ratings (Qi) and required road works (2018, p.14)

Ratings of Q4 to Q6 denote indeterminate and inconsistent visual inspection and deflection results. ANNEX III provides a process for reassessing a road’s rating to reclassify it either as Q7-Q8 or Q2-Q3. Ratings of Q7 to Q9 indicate that rehabilitation such as structural overlay is needed. For further detail on how this paper uses Qi ratings in SD, see Fig. 4 in the SFD section. This figure presents the ratings as stocks and demonstrates how they affect each other.

Road Network and Isolated Sections

The RR33 road section goes from the intersection of the RR33 and the RRP (La Goulette road section) to the entrance of the RRP. This road section is around 730 m long and 15 m wide. Road section 1 is represented in green, goes from the Port's entrance to road section 2, and is 380 m long and 15 m wide. Next, road section 2 is represented in blue and is 1,550 m long and 18 m wide. Road section 3, illustrated in yellow, is 1,500 m long by 14 m wide. Finally, road section 4 is shown in pink, and goes from the middle of road section 3 to the Port entrance. This section's dimensions are 890 m long and 14 m wide.

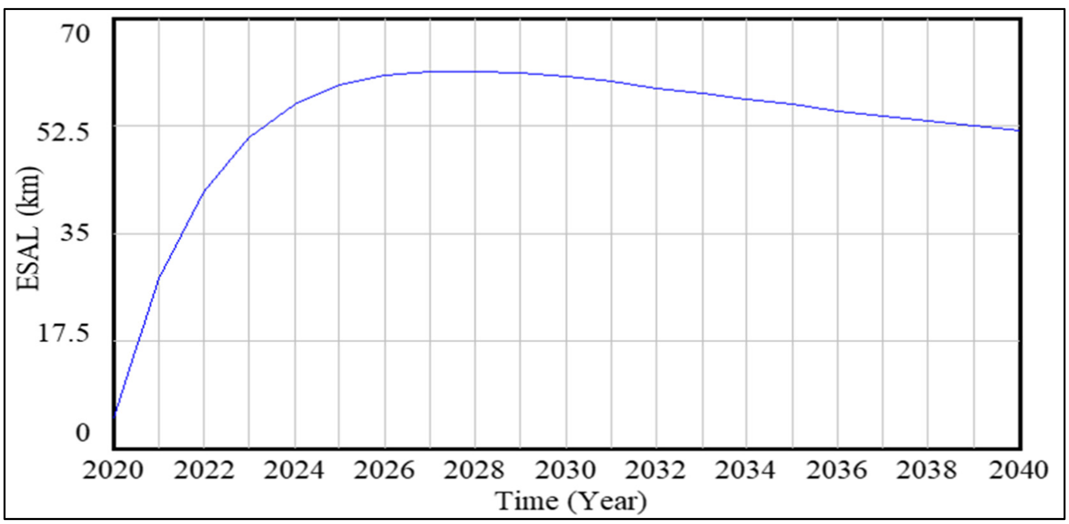


Figure- A-III-2 Number of km rehabilitated each year

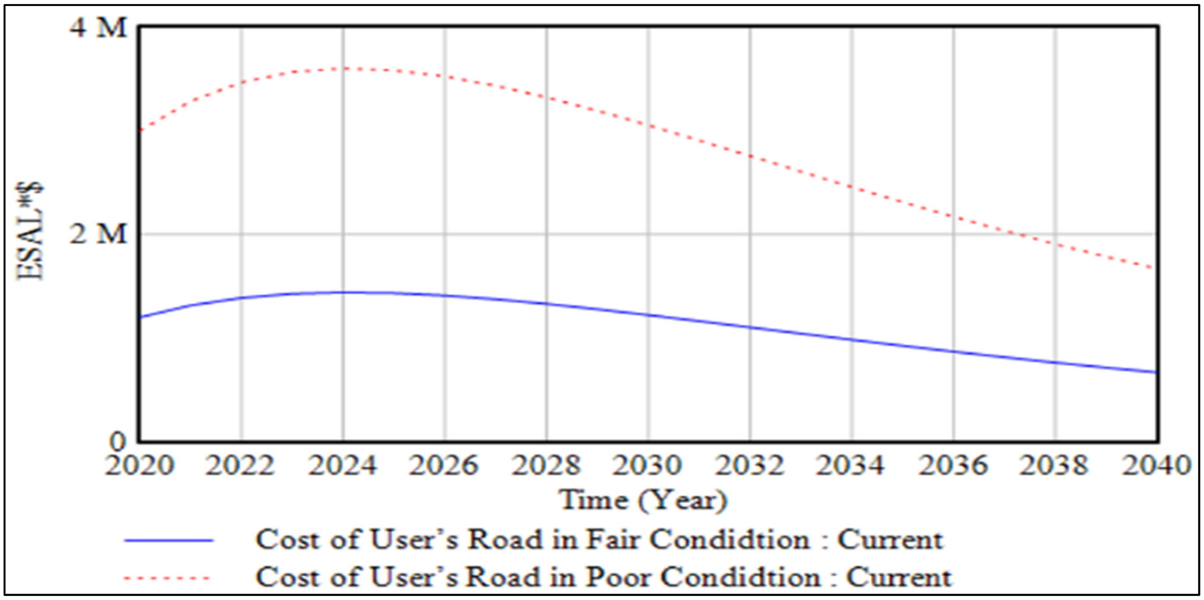


Figure- A-III-3 Model allows stakeholders to calculate user costs that reduced over 20 years on roads in fair condition due to increased rehabilitation

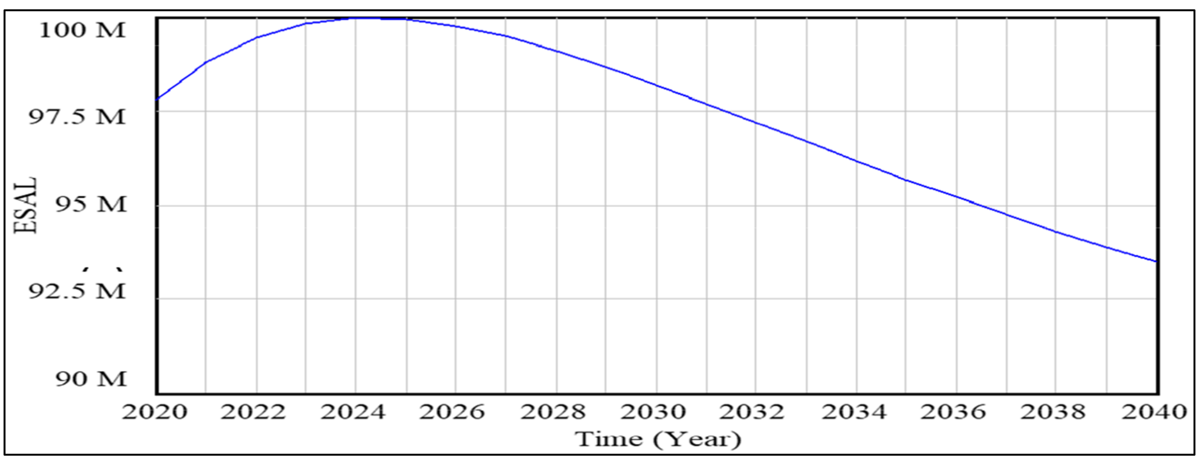
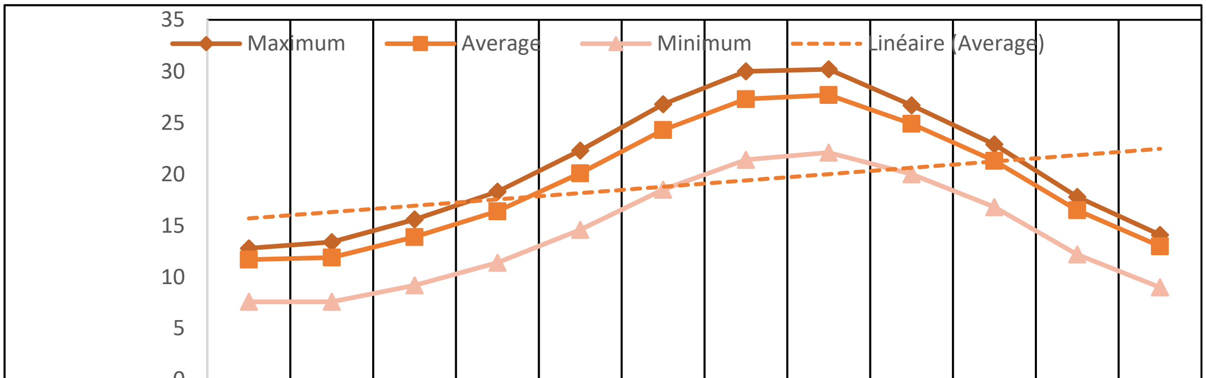


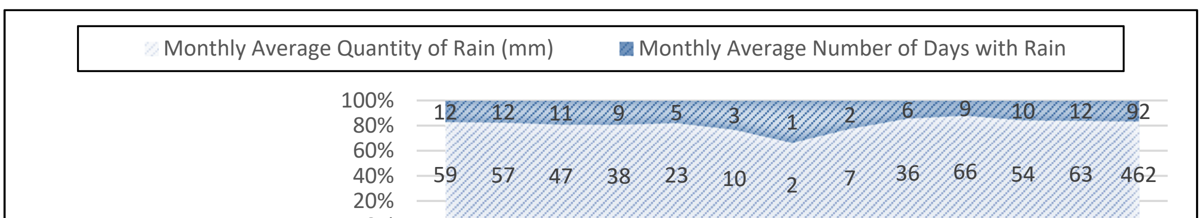
Figure- A-III-4 Road's transit traffic, the development of the RLZ, and the projected RRP extension. The ESAL steadily decrease after 100 million ESAL



	1	2	3	4	5	6	7	8	9	10	11	12
Maximum	12,8	13,4	15,6	18,3	22,3	26,8	30	30,2	26,7	22,9	17,8	14,1
Average	11,7	11,9	13,9	16,4	20,1	24,3	27,3	27,7	24,9	21,3	16,5	13
Minimum	7,6	7,6	9,2	11,4	14,6	18,5	21,4	22,1	20	16,8	12,2	9

Figure- A III- 5 Historical normalized monthly average temperature (MAT) for the region.

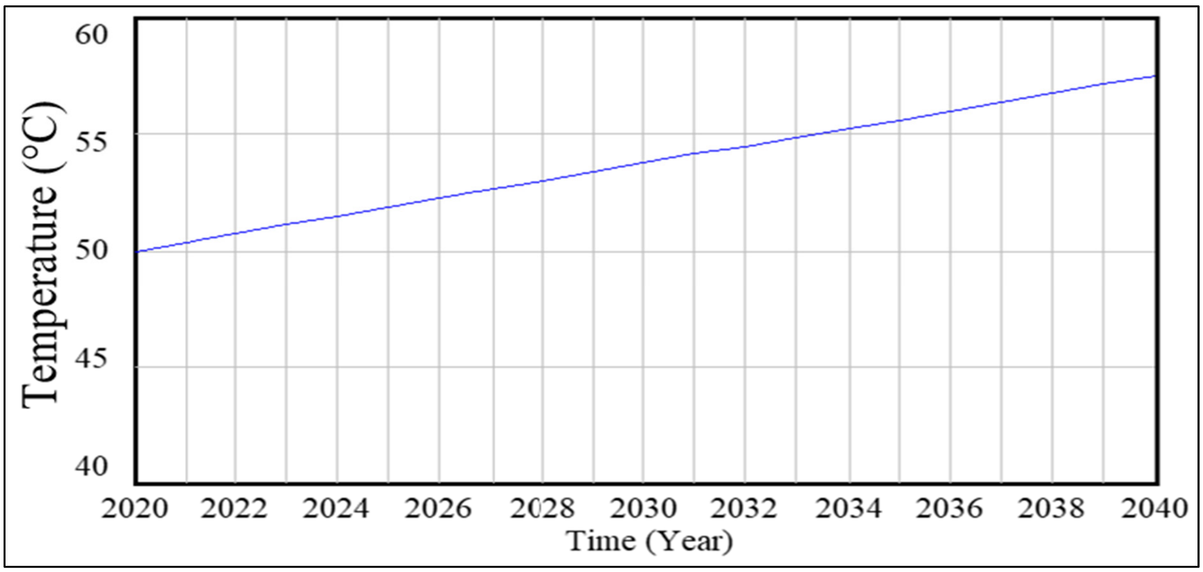
The studied zone has the following air temperature distributions: July and August are the warmest months, while January is the coldest; the minimum MAT varies between 7.6 and 22.1°C; and the maximum MAT fluctuates between 12.8 and 30.2°C (Carthage Station 2001-2020 2021).



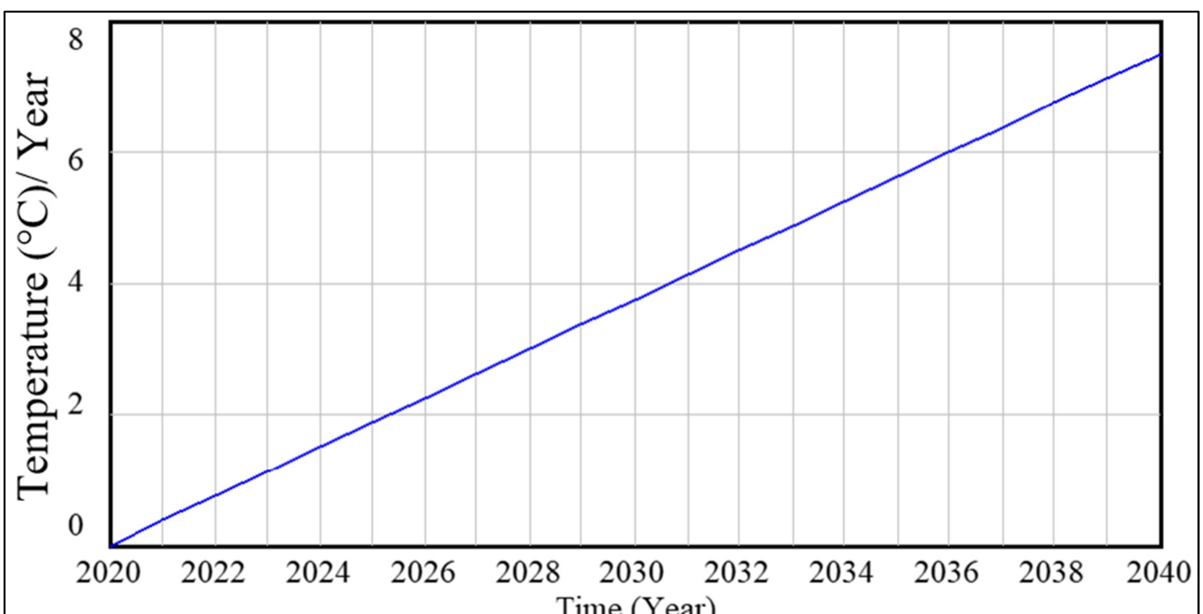
	January	February	March	April	May	June	July	August	September	October	November	December	Total
Monthly Average Number of Days with Rain	12	12	11	9	5	3	1	2	6	9	10	12	92
Monthly Average Quantity of Rain (mm)	59	57	47	38	23	10	2	7	36	66	54	63	462

Figure- A III- 6 Monthly Average Rain (MAR) for the region.

The data demonstrate that: the MAR varies between 2 mm and 66 mm; the monthly average number of days of rain fluctuates between 1 and 12 days; the yearly average number of days of rain is 92; the MAR is the lowest in July and the highest in October, December, and January; and the yearly average quantity of rainwater is 462 mm (Carthage Station 2001-2020 2021).



(a)



(b)

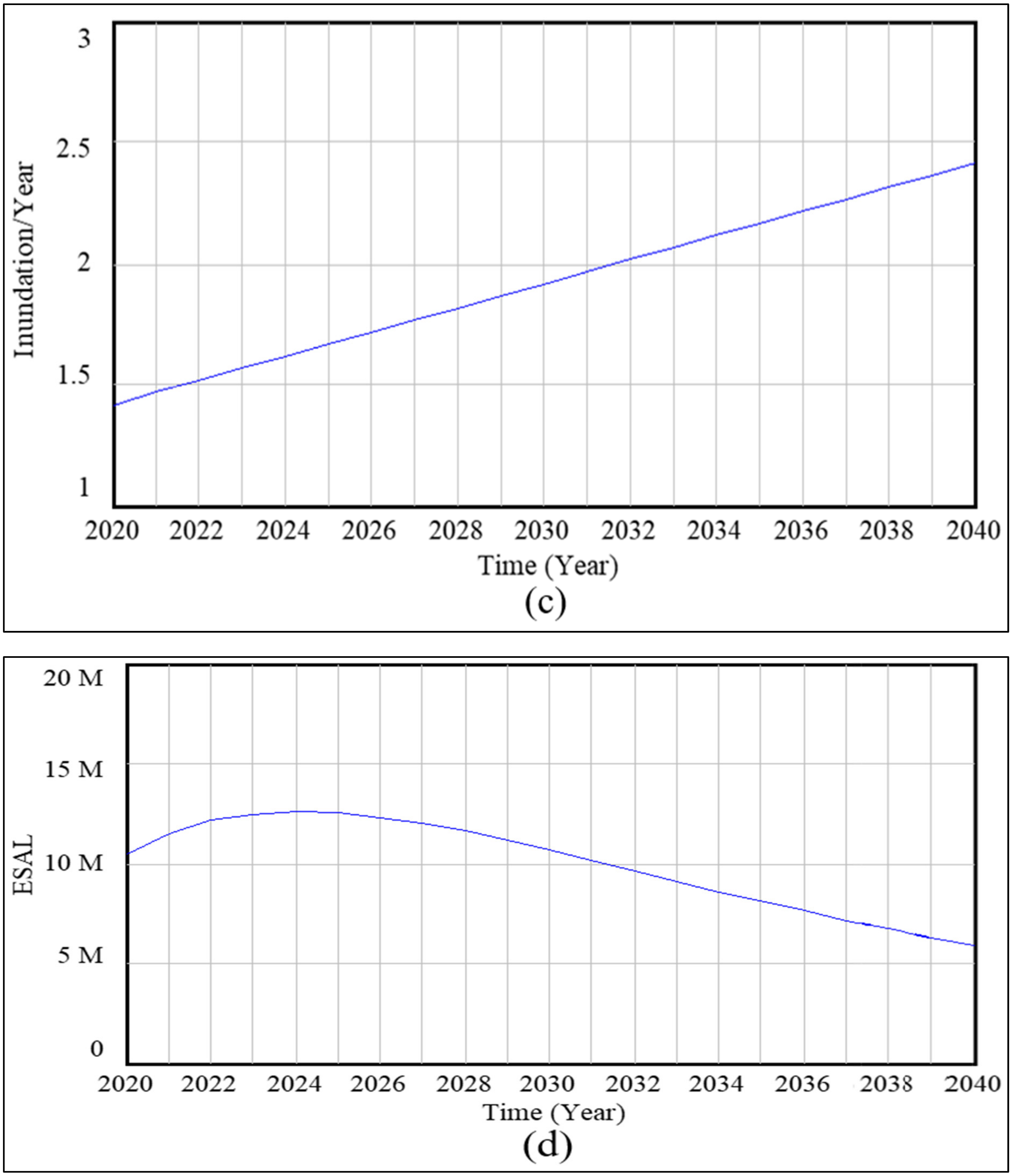


Figure- A III- 7 Projected climate change impacts on Radès Road Port

Figure-A III Shows the effects of 20 years of projected climate change on RRP pavement: **(a)** pavement temperature increase over time; **(b)** increase of the average annual pavement temperature over time; **(c)** increase of the average annual inundation rate over time; and **(d)** overall decrease of equivalent single axle load (ESAL) over time.

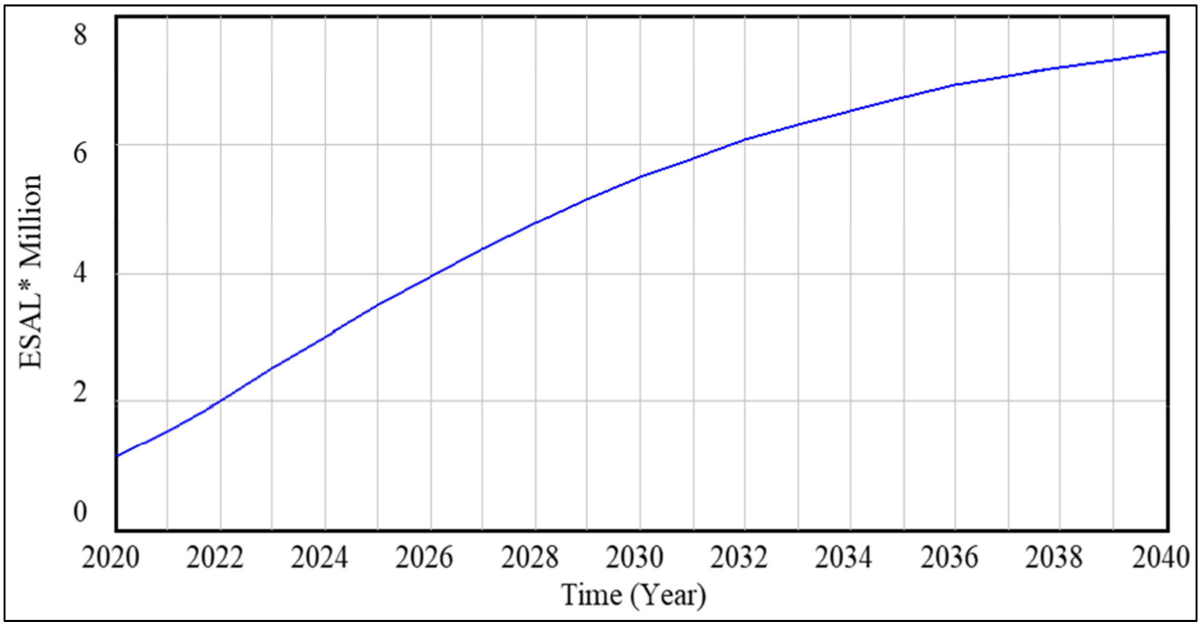


Figure- A III- 8 Growth of ESAL during the entire study period (2020-2040).

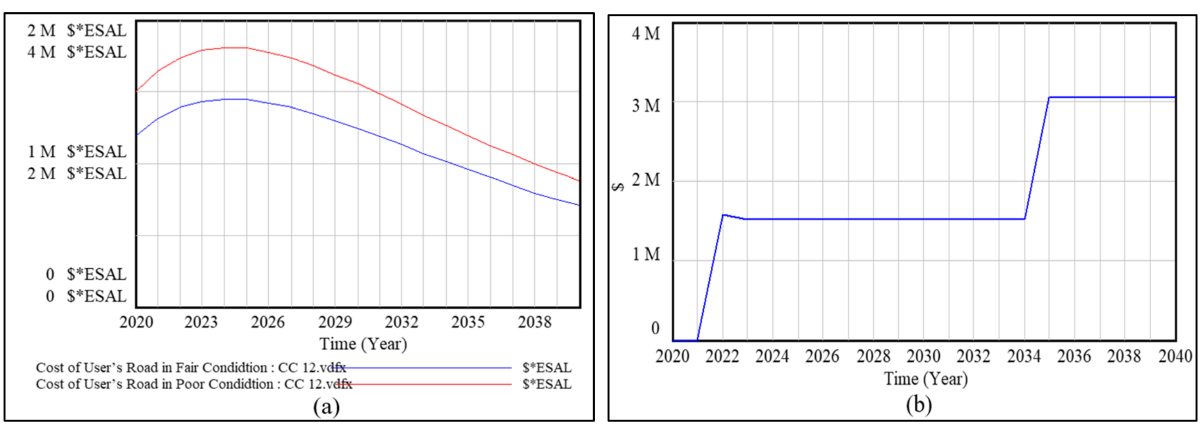


Figure- A III- 9 (a) Roads in fair condition have a maximum user cost,
(b) Net Present Value

This result confirms a) Roads in fair condition have a maximum user cost of approximately $1.8 million in 2025, dropping to $700,000 by 2040; and (b) net present value (NPV) cash flow grows from $0 to $3 million that the proposed interventions improve the RRP's overall NPV over the 20-year study period and that the model is a fiscally sound investment resulting in financial gain and improved road function.

Budgets and Costs of Road Interventions

Both scenarios' associated costs are shown in. It shows each candidate road section's total budget with and without safety for the alternative pavement solutions and the associated ERRs.

Table-A III 1 Total budget and economic rate return (ERR) for the RR33.

Candidate Road	Safety	Recommended structure	Total Budget (USD)	ERR - Traffic growth rate of 3%	ERR - Traffic growth rate of 5%
RR33 including bridge	Yes	Rigid Pavement (*)	1 677 065 $	22%	34%
	No	Rigid Pavement	1 604 065 $	22%	35%
Road section 1	Yes	Rigid Pavement	521 623 $	14%	16%
	No	Rigid Pavement	483 623 $	15%	17%
Road section 2	Yes	Rigid Pavement	2 279 472 $	9%	20%
	No	Rigid Pavement	2 124 472 $	10%	21%
Road section 3	Yes	Milling + Resurfacing (**)	541 463 $	15%	31%
	No	Milling + Resurfacing	391 463 $	27%	46%
Road section 4	Yes	Rigid Pavement	1 146 182 $	10%	13%
	No	Rigid Pavement	1 057 182 $	10%	14%

TOTAL COST WITH SAFETY	6 165 805 $
TOTAL COST WITHOUT SAFETY	5 660 805 $

Budget for five candidate road sections: 6,200,000 USD

Definition of Eq. 1

$$ESAL = AADT * V_L * CAM * N * f * L \quad \text{(A III- 1)}$$

Where AADT represents the annual average daily traffic in 2020 (vehicles/day): 6,000 trucks per day for the RR33 road section and 2,500 trucks per day for the other road sections in the RRP. V_L is the percentage of heavy vehicles (trucks/other) in the lane under study: 100%. CAM represents the truck factor (ESAL/truck) assumed to be equal to 1.5 (SETRA & LCPC, 1998). N is the estimated number of days the road supports this AADT, expressed in days per year. The f variable represents the heavy vehicle growth rate, for which the traffic counts were calculated in 2020. Finally, L is the lane distribution factor of 80% since the design is geared toward the aggressively loaded road section (RR33).

ANNEX IV

Model Equations for Chapter (5) S (1-77)

S1. AADT for Current Year= 1768, Units: Percent

S2. Age 2 to 3= 35.5, Units: Year

S3. Age 3 to 4= 22.5, Units: Year

S4. Age 4 to 5= 18, Units: Year

S5. Age 5 to 6= 15.5, Units: Year

S6. Age 6 to 7= 10, Units: Year

S7. Age1= 50, Units: Year

S8. Age7to1= 28, Units: Year

S9. Average Pavement Life = A FUNCTION OF (Effective Resilient Modulus of Subgrade Soil, ESAL, Increase in Cost of Road Construction and Maintenance HP, NPV of Cash Flow, Rate of Change in Average Annual Rainfall, Rate of Increase in Temperature, -Total Budget, Total Cost), Units: ESAL/Year

S10. Average time to Rehabilitate the Road= 1.2, Units: Dmnl

S11. CAM truck factor ESAL truck= 1.5, Units: 1/Year

S12. Cost of User's Road in Fair Condition= Cost per User of Road in Fair Condition*Road in Poor Condition Q5 to Q6, Units: ESAL*$

S13. Cost of User's Road in Poor Condition= Road in Poor Condition Q5 to Q6*Cost per User of Road in Poor Condition, Units: ESAL*$

S14. Cost per User of Road in Fair Condition= 20000, Units: $

S15. Cost per User of Road in Poor Condition= 50000, Units: $

S16. Cracking Disintegration and Potholes= Road in Fair Condition Q3 to Q4/Age 5 to 6, Units: ESAL/Year

S17. Decrease in Cost of Road Construction and Maintenance HP= -0.03, Units: 1/Year

S18. Detected Time for Road Failures= ESAL + Average Pavement Life, Units: 1/Year

S19. Discount Rate= 0.05, Units: 1/Year

S20. Effective Inundation= Increase in Cost of Road Construction and Maintenance HP *Number of Inundations per Year/Rate of Change in Seawater Level*Decrease in Cost of Road Construction and Maintenance HP, Units: Percent/Year

S21. Effective Inundation plus Temperature Adjusted Modulus of HMA= INTEG (Temperature Adjusted Modulus of HMA + Effective Inundation, 0.5) Units: Percent

S22. Effective Resilient Modulus of Subgrade Soil= 0.000265*(12+((Months with HP Saturation Adjustor for Maximum of 8 months)/12+8.69e+06*Months with HP Saturation Adjustor for Maximum of 8 months / 12)) Units: Percent

S23. ERR= STEP (2025, 2040) *NPV of Cash Flow Units: $/Year

S24. ESAL= AADT for Current Year*VL percentage of heavy vehicles*CAM truck factor ESAL truck *N number of days*f Heavy Vehicle Growth Rate *L lane distribution factor Units: 1/Year

S25. Base scenario 650,000 3% 10.2 x 106 Aggressive scenario 910,000 5% 12.0 x 1000000

S26. f Heavy Vehicle Growth Rate= 0.03 Units: 1

S27. FINAL TIME = 2040 Units: Year The final time for the simulation.

S28. Fiscal Period= STEP (2022, 2035) Units: 1/Year

S29. Fiscal Period Offset= 2025 Units: Dmnl

All values are discounted as if they had occurred at the point in the fiscal period specified by this offset. Use 1.0 to discount at the end of the period (the most common usage), .5 for the middle and 0 for the beginning.

S30. Fiscal Start= Time Units: Year

The values for fiscal period, fiscal start and fiscal period offset are all used to initialize the function. Changes to these values at later times during the simulation will not have any impact on the behavior of the function. This is why it is fine to use Time for f start.

S31. GHG= Road in Poor Condition Q5 to Q6+ (Total Cost), Units: ESAL/$

S32. Hot-Mix Asphalt= INTEG (Hot-Mix Asphalt Use Per Km1+ (Hot-Mix Asphalt Use Rate), 5) Units: C 1e + 20 (this number has been chosen arbitrarily)

S33. Hot-Mix Asphalt Use Per Km1= 0.636*Decrease in Cost of Road Construction and Maintenance HP*Hot-Mix Asphalt Units: C/Year

S34. Hot-Mix Asphalt Use Rate= Hot-Mix Asphalt*Increase in Cost of Road Construction and Maintenance HP Units: C/Year

S35. Increase in Cost of Road Construction and Maintenance HP= 0.06

Units: 1/Year hundred percent (HP) 100%

Increase in HP Saturation Months= (0.071* Rate of Change in Average Annual Rainfall)

Units: Percent/Year

hundred percent (HP) 100%

S36. Increase in Number of Inundations per Year= 10.695*(Rate of Change in Seawater Level+1) *(Increase Rate Number of Flood Causing Hurricanes) Units: Percent/Year

S37. Initial Road Degradation= Road in Very Good Condition Q1 to Q2/Age1 Units: ESAL/Year

S38. INITIAL TIME = 2020 Units: Year "The initial time for the simulation".

S39. Investment= 70000 Units: $

S40. L lane distribution factor= 0.8 Units: 1/Year

S41. Max Pavement Temperature= INTEG (Temperature Increase, 50) Units: Percent (maximum temperature at project location)

S42. Months with HP Saturation= INTEG (Increase in HP Saturation Months, 0.0056) Units: Percent hundred percent 100% (HP)

S43. Months with HP Saturation Adjustor for Maximum of 8 months= IF THEN ELSE (Months with HP Saturation<=8, Months with HP Saturation ,8) Units: Percent 100%

S44. N number of days = 1 Units: Year

S45. Net Cash Flow= Investment/Start Time*PULSE (Start Time, TIME STEP) +STEP (Revenue, Start Time) Units: $/Year

S46. NPV of Cash Flow= PULSE TRAIN (Net Cash Flow, Discount Rate, Fiscal Period Offset, Fiscal Start) + (Fiscal Period+ Fiscal Start) *Net Cash Flow, Units: $/Year

S47. Number of Inundations per Year= INTEG (Increase in Number of Inundations per Year, 0.267 + 1+ 0.15) Units: Percent

S48. Periodic Road Maintenance Per KM Required = A FUNCTION OF (Age 4 to 5, Detected Time for Road Failures, Road in Fair Condition Q3 to Q4) Periodic Road Maintenance Per KM Required= IF THEN ELSE (Detected Time for Road Failures>1, Road in Fair Condition Q3 to Q4 /Age 4 to 5,0) Units: ESAL/Year

S49. Q7to Q9 Quality Ratings = A FUNCTION OF (Age 6 to 7, Average time to Rehabilitate the Road, Detected Time for Road Failures, Road in Poor Condition Q5 to Q6) Q7to Q9 Quality Ratings= IF THEN ELSE (Detected Time for Road Failures>1, Road in Poor Condition Q5 to Q6 /Age 6 to 7,0) *Average time to Rehabilitate the Road Units: ESAL/Year

S50. Rate Detected Time for Road Failures= IF THEN ELSE (Detected Time for Road Failures>1, Road in Very Good Condition Q1 to 2 /Age7to1,0) Units: ESAL/Year

S51. Rate of Change in Average Annual Rainfall= 0.28189, Units: Percent/Year

S52. Rate of Change in Max Air Temperature= MIN (50, 80), Units: Percent/Year

S53. Rate of Change in Seawater Level= 0.0093 Units: 1/Year

S54. Increase Rate Number of Flood Causing Hurricanes= 0.00462 Units: Percent/1

S55. Rate of Increase in Temperature= 100 Units: Dmnl

S56. Rehabilitated= IF THEN ELSE (Total Budget>=50000, Rehabilitation Q7/Road Treatment Delayed, 0) Units: ESAL/Year

S57. Rehabilitation Budget Portion= NPV of Cash Flow + ERR Units: $/Year

S58. Rehabilitation Q7= INTEG (Q7to Q9 Quality Ratings + Routine Maintenance Required + Periodic Road Maintenance Per KM Required +Rate Detected Time for Road Failures-Rehabilitated, 50) Units: ESAL

S59. Required Road Sustainable Solutions= GHG/Total Roads, Units: ESAL

S60. Revenue=750, Units: $/Year

S61. Road in Fair Condition Q3 to Q4= INTEG (Structural Fatigue-Cracking Disintegration and Potholes-Periodic Road Maintenance Per KM Required, 200) Units: ESAL

S62. Road in Good Condition Q2 to Q3= INTEG (Initial Road Degradation-Routine Maintenance Required-Structural Fatigue, 100) Units: ESAL

S63. Road in Poor Condition Q5 to Q6= INTEG (Cracking Disintegration and Potholes-Q7to Q9 Quality Ratings, 60), Units: ESAL

S64. Road in Very Good Condition Q1 to Q2= INTEG (Rehabilitated-Initial Road Degradation-Rate Detected Time for Road Failures,40) Units: ESAL

S65. Road Treatment Delayed= 3, Units: Year

S66. Routine Maintenance Required= IF THEN ELSE (Detected Time for Road Failures>1, Road in Good Condition Q2 to Q3 /Age 3 to 4,0) Units: ESAL/Year

S67. SAVEPER = TIME STEP Units: Year [0,] The frequency with which output is stored.

S68. Start Time= 2022 Units: Year

S69. Structural Fatigue= Road in Good Condition Q2 to Q3/Age 2 to 3, Units: ESAL/Year

S70. Temperature Adjusted Minimum HMA Modulus= 0.01558 -(0.0165) * Max Pavement Temperature Units: Percent

S71. Temperature Adjusted Modulus of HMA= Months with HP Saturation Adjustor for Maximum of 8 months*Rate of Change in Average Annual Rainfall /Temperature Adjusted Minimum HMA Modulus + Effective Inundation plus Temperature Adjusted Modulus of HMA Units: Percent/Year

S72. Temperature Increase= MAX (0.5,0.75) *Rate of Change in Max Air Temperature/Rate of Increase in Temperature Units: Percent/Year

S73. TIME STEP = 1 Units: Year [0,?] The time step for the simulation.

S74. Total Budget= MAX (Rehabilitation Budget Portion, 50000) –PV of Cash Flow, Units: $/Year

S75. Total Cost= Cost of User’s Road in Fair Condition +Cost of User’s Road in Poor Condition Units: ESAL*$

S76. Total Roads= Road in Fair Condition Q3 to Q4+Road in Good Condition Q2 to Q3+Road in Poor Condition Q5 to Q6 +Road in Very Good Condition Q1 to Q2 +Rehabilitation Q7 Units: ESAL

S77. VL percentage of heavy vehicles = 1, Units: %

ANNEX V

SIDRA intersection output

For each simulation, the capacity per hour *(number of vehicles and % of heavy vehicles)*, based on traffic counts performed in April 2020 *(as a SIDRA Intersection input)*, the average control delay per vehicle *(output)*, the degree of saturation *(output)*, the level of service *(output)* and the roundabout performance measures *(in particular the degree of saturation and the effective intersection capacity)* are provided.

For the South roundabout, located at the intersection of the RR33, Road section 1 and Road section 4:

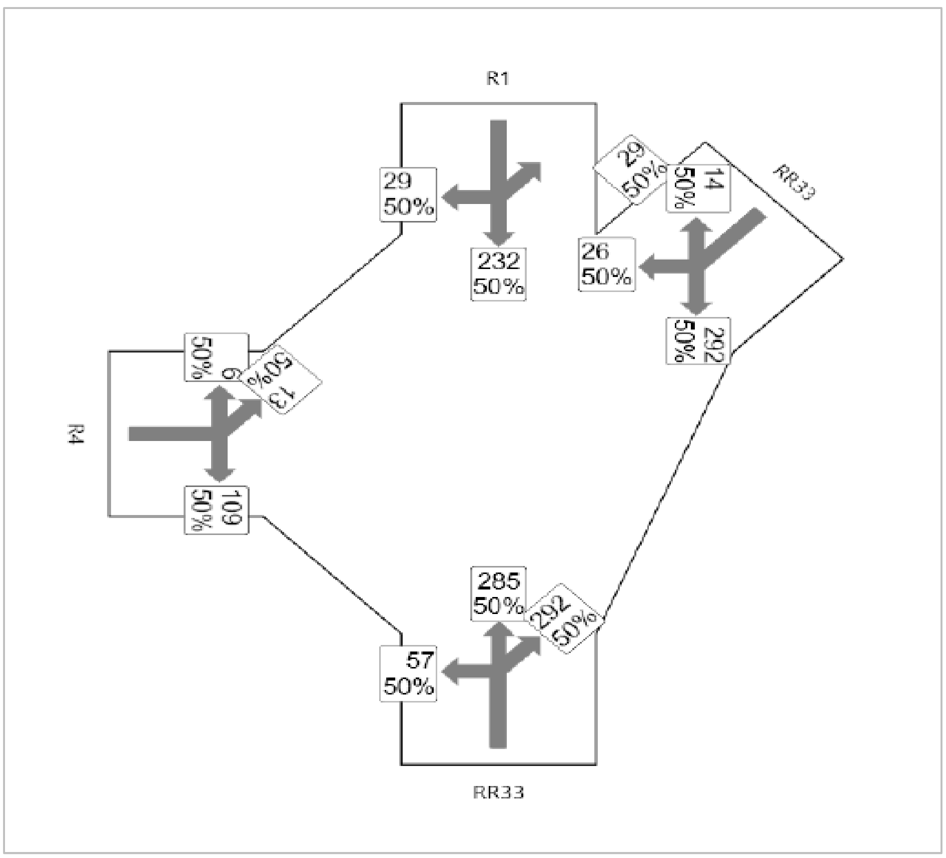


Figure-A III- 6 1 Input: Capacity per hour
number of vehicles and % of heavy vehicles based on traffic
counts performed in April 2020

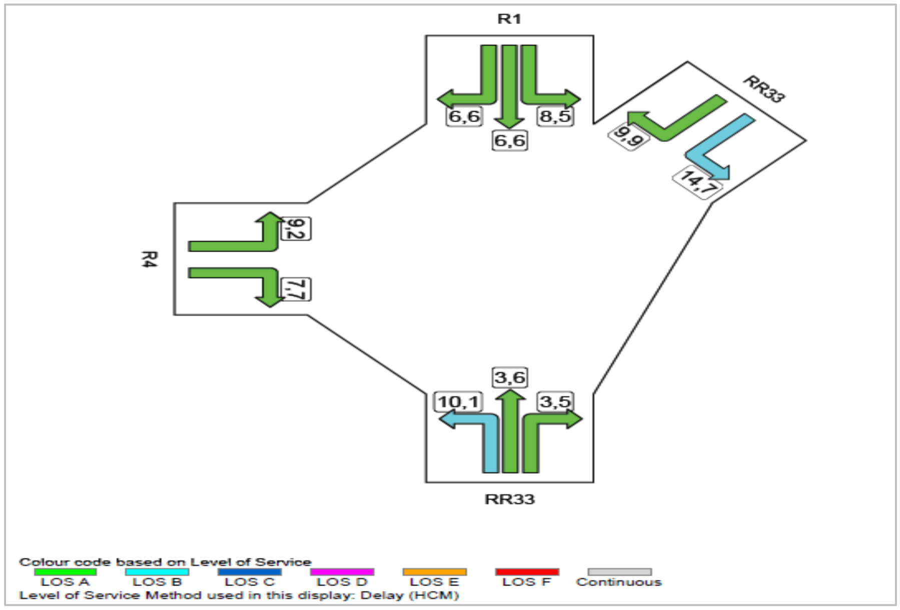


Figure-A III- 6 2 Average control delay per vehicle
(in seconds)

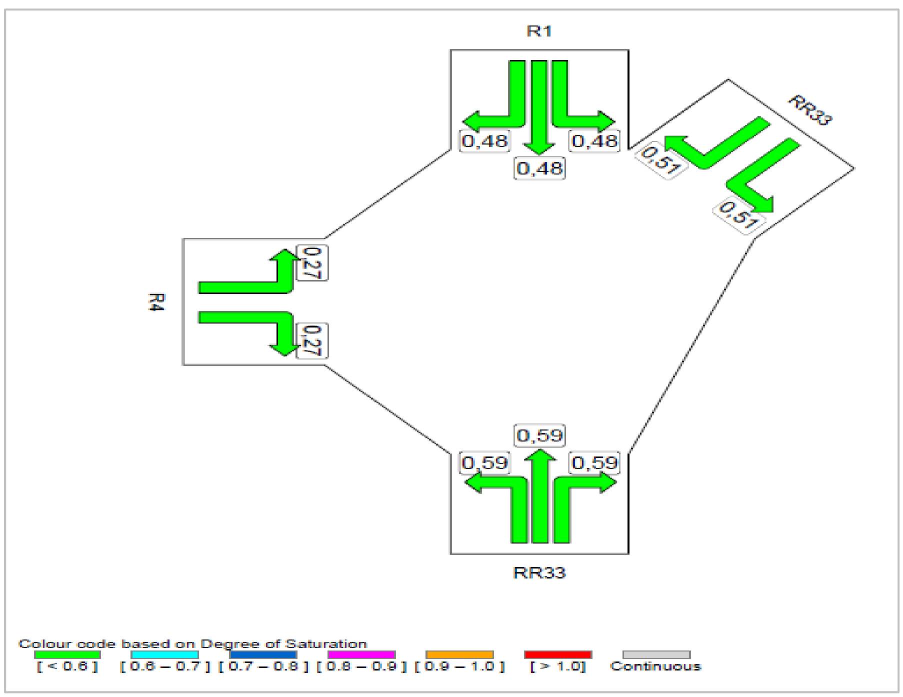


Figure-A III- 6 3 Degree of saturation (in %)

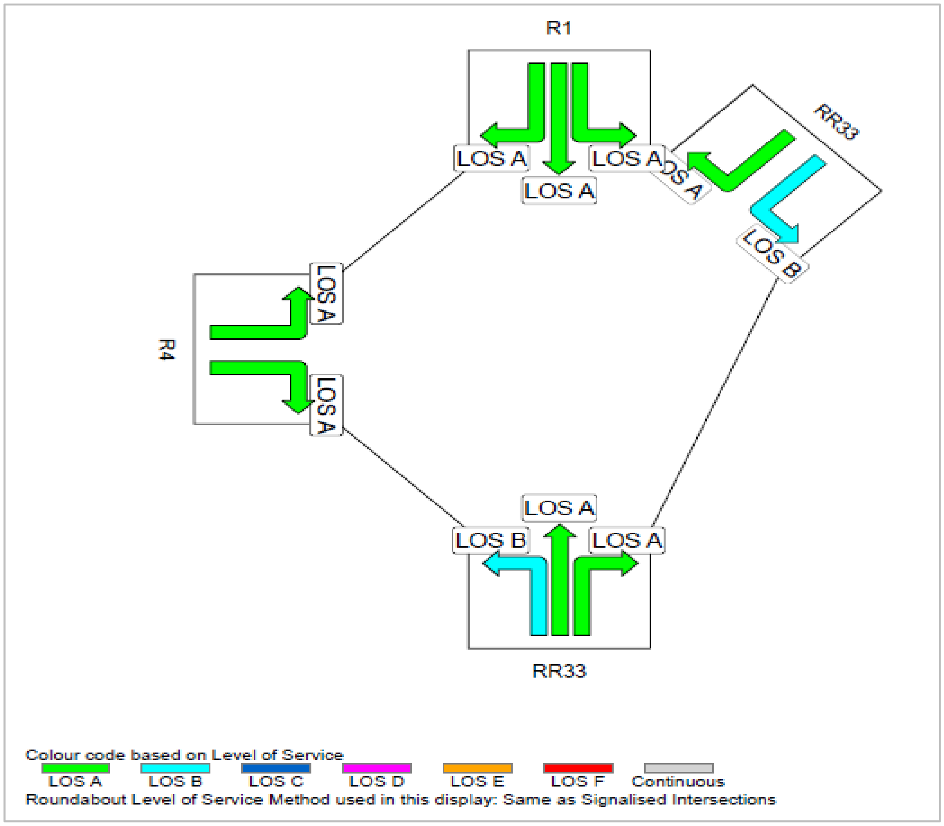


Figure-A III- 6 4 Level of service based on degree of saturation and average control delay per vehicle

Intersection Performance - Hourly Values		
Performance Measure	**Vehicles**	**Persons**
Demand Flows (Total)	1384 veh/h	1661 pers/h
Percent Heavy Vehicles	50,0 %	
Degree of Saturation	0,587	
Practical Spare Capacity	44,6 %	
Effective Intersection Capacity	[illegible] veh/h	
Control Delay (Total)	2,86 veh-h/h	3,43 pers-h/h
Control Delay (Average)	7,4 sec	7,4 sec
Control Delay (Worst Lane)	14,1 sec	
Control Delay (Worst Movement)	14,7 sec	14,7 sec
Geometric Delay (Average)	3,3 sec	
Stop-Line Delay (Average)	4,1 sec	
Level of Service (Aver. Int. Delay)	LOS A	
Level of Service (Worst Movement)	LOS B	
Level of Service (Worst Lane)	LOS B	
95% Back of Queue - Vehicles (Worst Lane)	6,8 veh	
95% Back of Queue - Distance (Worst Lane)	68,4 m	
Total Effective Stops	912 veh/h	1095 pers/h
Effective Stop Rate	0,66 per veh	0,66 per pers
Proportion Queued	0,64	0,64
Performance Index	33,0	33,0
Travel Distance (Total)	805,9 veh-km/h	967,1 pers-km/h
Travel Distance (Average)	582 m	582 m
Travel Time (Total)	22,2 veh-h/h	26,7 pers-h/h
Travel Time (Average)	57,9 sec	57,9 sec
Travel Speed	36,2 km/h	36,2 km/h

Figure-A III- 6 5 For the North roundabout, located at the intersection of

Road section 1, Road section 2 and Road section 3

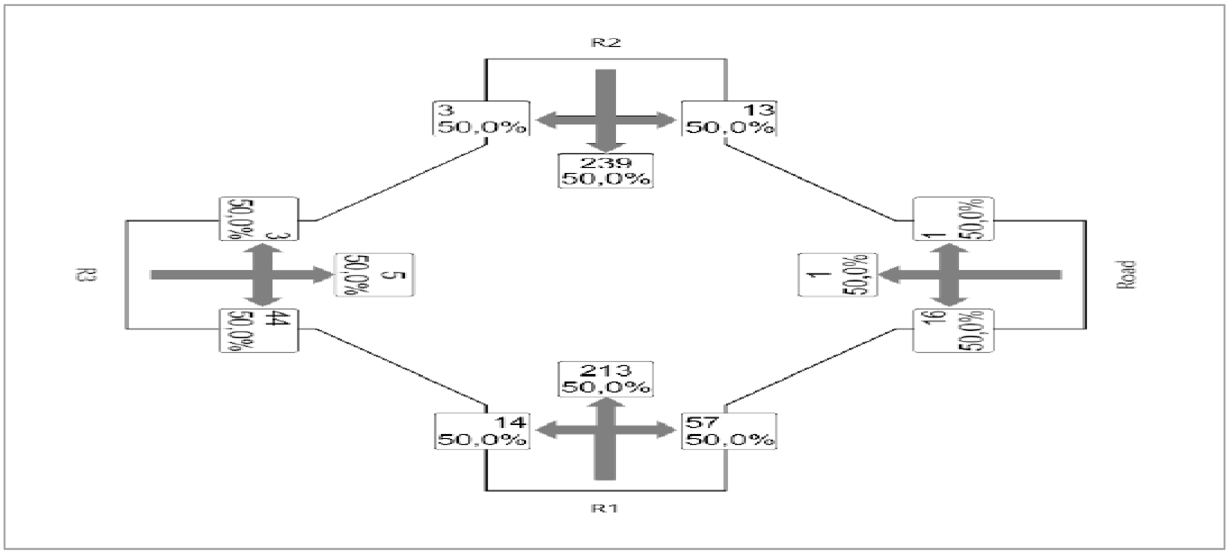


Figure-A III- 6 6 Input Capacity per hour (number of vehicles and % of heavy vehicles), based on traffic counts performed in April 2020

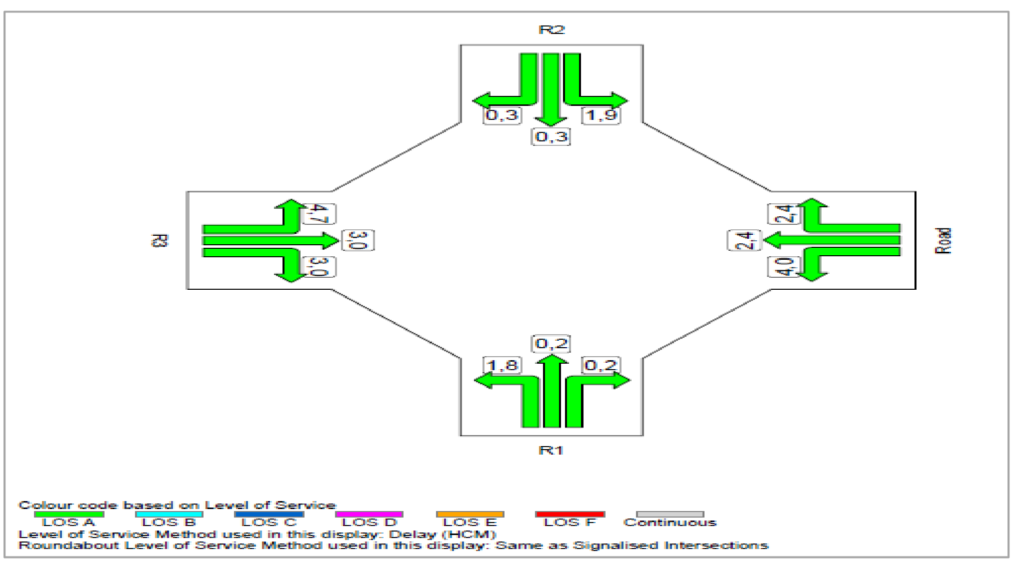
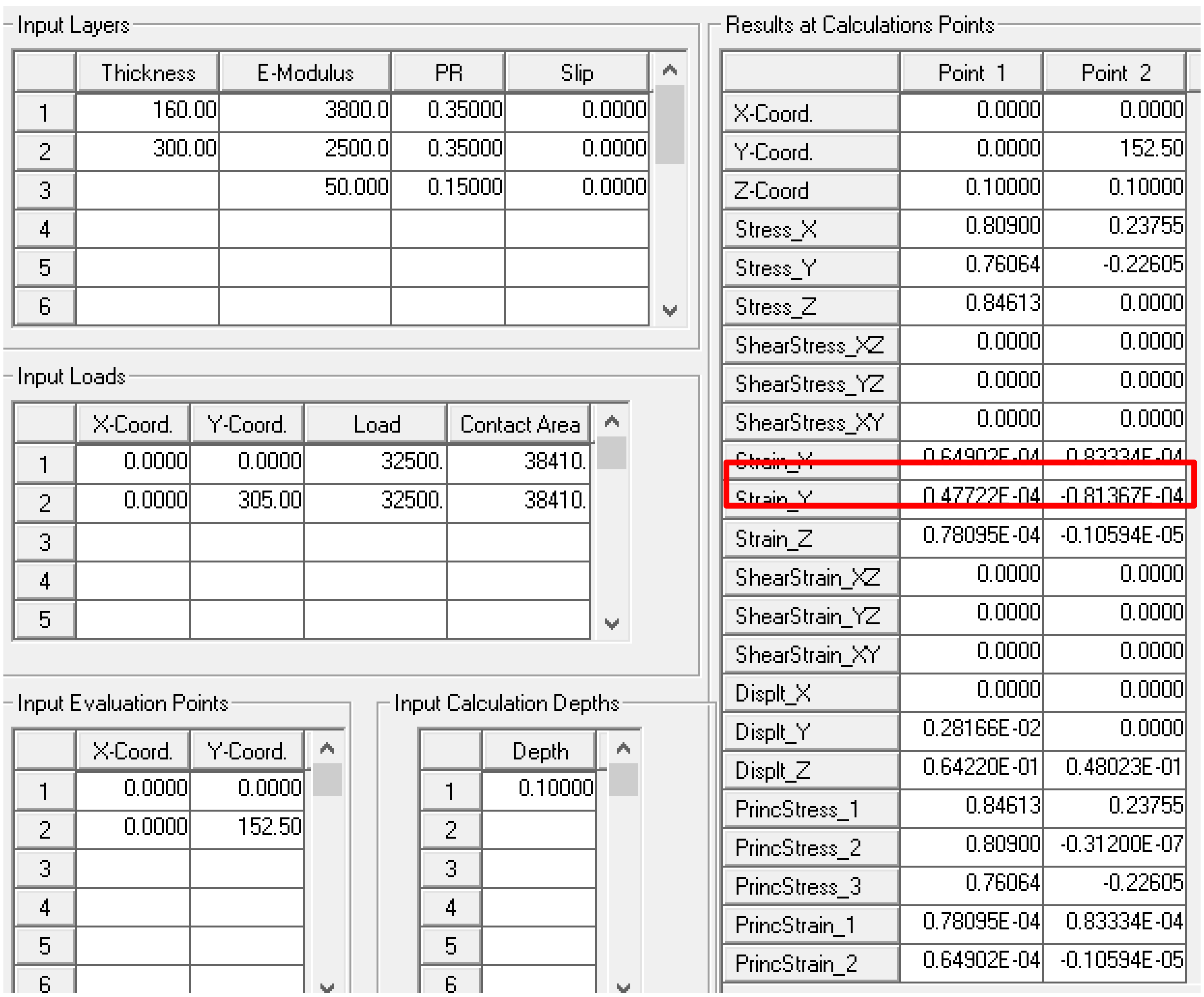


Figure-A III- 6 7 Average control delay per vehicle (in seconds)

ANNEX VI

Failure in compression at the top of the asphalt concrete



Input Layers

	Thickness	E-Modulus	PR	Slip
1	160.00	3800.0	0.35000	0.0000
2	300.00	2500.0	0.35000	0.0000
3		50.000	0.15000	0.0000
4				
5				
6				

Input Loads

	X-Coord.	Y-Coord.	Load	Contact Area
1	0.0000	0.0000	32500.	38410.
2	0.0000	305.00	32500.	38410.
3				
4				
5				

Input Evaluation Points

	X-Coord.	Y-Coord.
1	0.0000	0.0000
2	0.0000	152.50
3		
4		
5		
6		

Input Calculation Depths

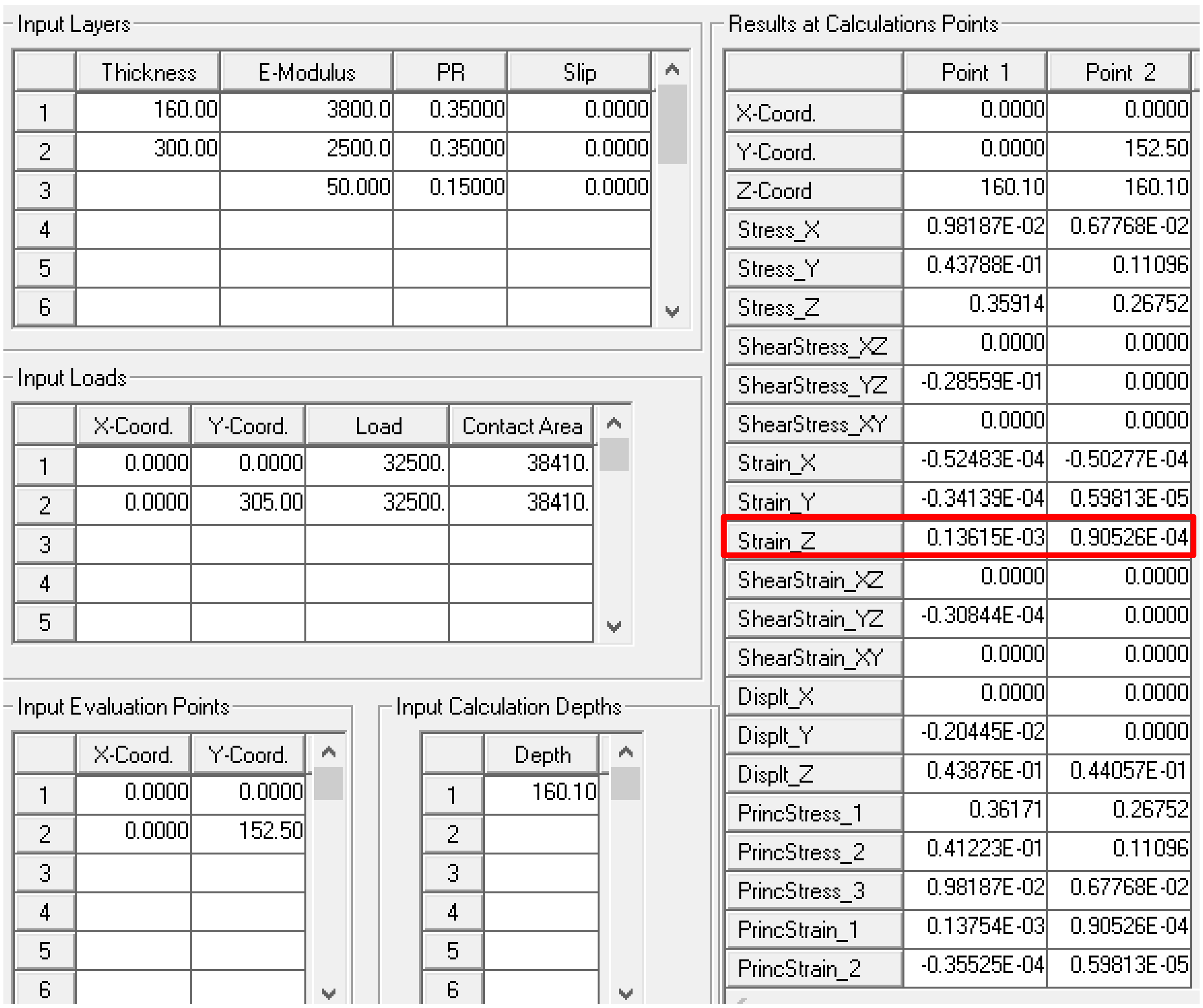
	Depth
1	0.10000
2	
3	
4	
5	
6	

Results at Calculations Points

	Point 1	Point 2
X-Coord.	0.0000	0.0000
Y-Coord.	0.0000	152.50
Z-Coord	0.10000	0.10000
Stress_X	0.80900	0.23755
Stress_Y	0.76064	-0.22605
Stress_Z	0.84613	0.0000
ShearStress_XZ	0.0000	0.0000
ShearStress_YZ	0.0000	0.0000
ShearStress_XY	0.0000	0.0000
Strain_X	0.64902E-04	0.83334E-04
Strain_Y	0.47722E-04	-0.81367E-04
Strain_Z	0.78095E-04	-0.10594E-05
ShearStrain_XZ	0.0000	0.0000
ShearStrain_YZ	0.0000	0.0000
ShearStrain_XY	0.0000	0.0000
Displt_X	0.0000	0.0000
Displt_Y	0.28166E-02	0.0000
Displt_Z	0.64220E-01	0.48023E-01
PrincStress_1	0.84613	0.23755
PrincStress_2	0.80900	-0.31200E-07
PrincStress_3	0.76064	-0.22605
PrincStrain_1	0.78095E-04	0.83334E-04
PrincStrain_2	0.64902E-04	-0.10594E-05

Figure-A III- 6 8 Compressive strains at the top of the asphalt concrete after one 13-ton axle load

Failure in compression at the top of the base course



Input Layers

	Thickness	E-Modulus	PR	Slip
1	160.00	3800.0	0.35000	0.0000
2	300.00	2500.0	0.35000	0.0000
3		50.000	0.15000	0.0000
4				
5				
6				

Input Loads

	X-Coord.	Y-Coord.	Load	Contact Area
1	0.0000	0.0000	32500.	38410.
2	0.0000	305.00	32500.	38410.
3				
4				
5				

Input Evaluation Points

	X-Coord.	Y-Coord.
1	0.0000	0.0000
2	0.0000	152.50
3		
4		
5		
6		

Input Calculation Depths

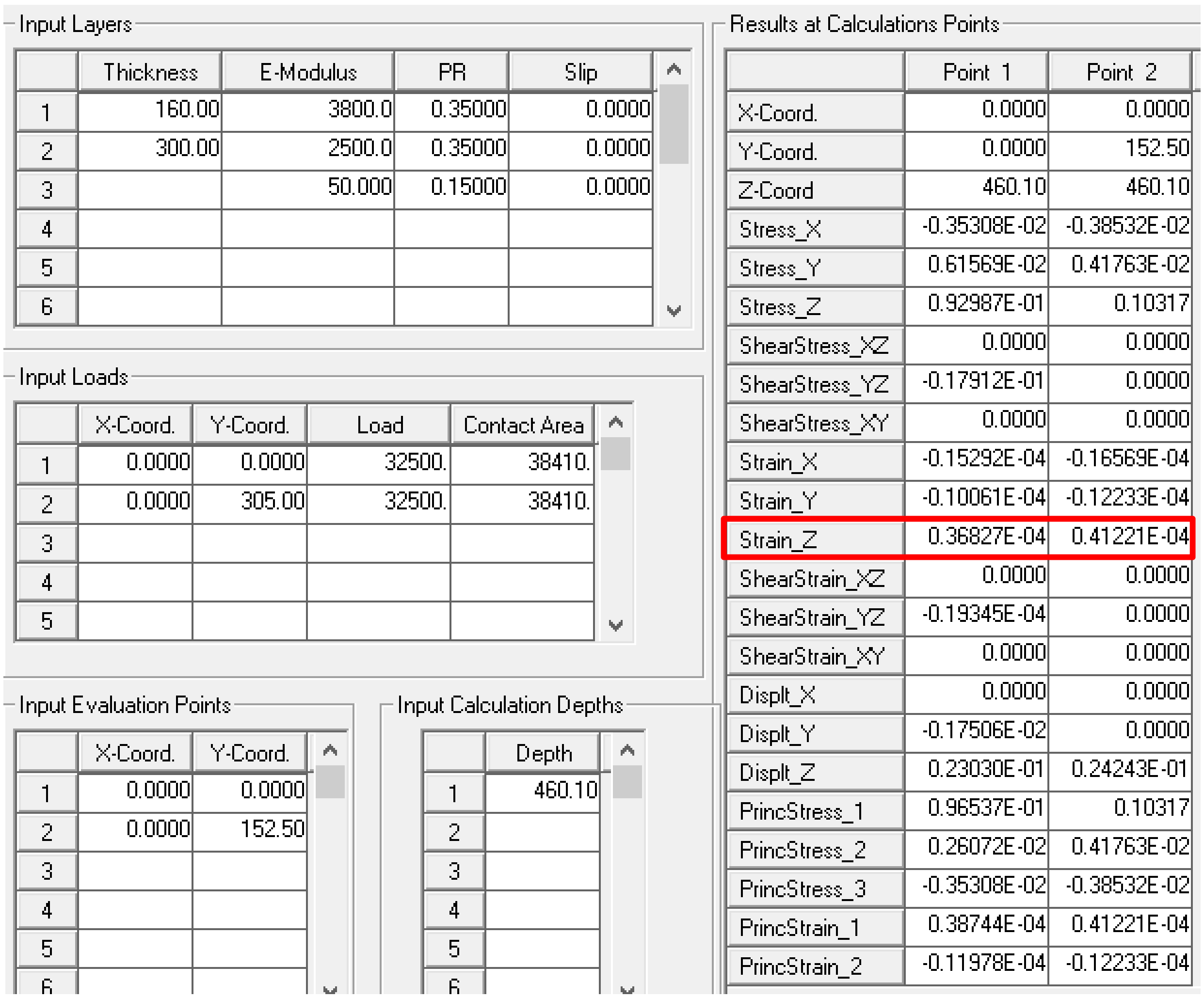
	Depth
1	160.10
2	
3	
4	
5	
6	

Results at Calculations Points

	Point 1	Point 2
X-Coord.	0.0000	0.0000
Y-Coord.	0.0000	152.50
Z-Coord	160.10	160.10
Stress_X	0.98187E-02	0.67768E-02
Stress_Y	0.43788E-01	0.11096
Stress_Z	0.35914	0.26752
ShearStress_XZ	0.0000	0.0000
ShearStress_YZ	-0.28559E-01	0.0000
ShearStress_XY	0.0000	0.0000
Strain_X	-0.52483E-04	-0.50277E-04
Strain_Y	-0.34139E-04	0.59813E-05
Strain_Z	0.13615E-03	0.90526E-04
ShearStrain_XZ	0.0000	0.0000
ShearStrain_YZ	-0.30844E-04	0.0000
ShearStrain_XY	0.0000	0.0000
Displt_X	0.0000	0.0000
Displt_Y	-0.20445E-02	0.0000
Displt_Z	0.43876E-01	0.44057E-01
PrincStress_1	0.36171	0.26752
PrincStress_2	0.41223E-01	0.11096
PrincStress_3	0.98187E-02	0.67768E-02
PrincStrain_1	0.13754E-03	0.90526E-04
PrincStrain_2	-0.35525E-04	0.59813E-05

Figure-A III- 6 9 Compressive strain at the top of the base course after one 13-ton axle load

Failure in compression at the top of the subbase



Input Layers

	Thickness	E-Modulus	PR	Slip
1	160.00	3800.0	0.35000	0.0000
2	300.00	2500.0	0.35000	0.0000
3		50.000	0.15000	0.0000
4				
5				
6				

Input Loads

	X-Coord.	Y-Coord.	Load	Contact Area
1	0.0000	0.0000	32500.	38410.
2	0.0000	305.00	32500.	38410.
3				
4				
5				

Input Evaluation Points

	X-Coord.	Y-Coord.
1	0.0000	0.0000
2	0.0000	152.50
3		
4		
5		
6		

Input Calculation Depths

	Depth
1	460.10
2	
3	
4	
5	
6	

Results at Calculations Points

	Point 1	Point 2
X-Coord.	0.0000	0.0000
Y-Coord.	0.0000	152.50
Z-Coord	460.10	460.10
Stress_X	-0.35308E-02	-0.38532E-02
Stress_Y	0.61569E-02	0.41763E-02
Stress_Z	0.92987E-01	0.10317
ShearStress_XZ	0.0000	0.0000
ShearStress_YZ	-0.17912E-01	0.0000
ShearStress_XY	0.0000	0.0000
Strain_X	-0.15292E-04	-0.16569E-04
Strain_Y	-0.10061E-04	-0.12233E-04
Strain_Z	0.36827E-04	0.41221E-04
ShearStrain_XZ	0.0000	0.0000
ShearStrain_YZ	-0.19345E-04	0.0000
ShearStrain_XY	0.0000	0.0000
Displt_X	0.0000	0.0000
Displt_Y	-0.17506E-02	0.0000
Displt_Z	0.23030E-01	0.24243E-01
PrincStress_1	0.96537E-01	0.10317
PrincStress_2	0.26072E-02	0.41763E-02
PrincStress_3	-0.35308E-02	-0.38532E-02
PrincStrain_1	0.38744E-04	0.41221E-04
PrincStrain_2	-0.11978E-04	-0.12233E-04

Figure-A III- 6 10 Compressive strains at the top of the subbase after one 13-ton axle load

Allowable number of repetitions to prevent compression failure of the subgrade is calculated with the equation provided below:

$$N_f = 1.365 x 10^{-9} (\varepsilon_c)^{-4.477} \quad (11.0)$$

Where;

N_f = Number of load applications to failure

ε_c = Vertical Compressive strain at the bottom of asphalt bound layer

Figure-A III- 6 11 Asphalt Institute Equation to determine structural fatigue life based on compressive strain (Ekwulo and Eme 2009)

We assume that the Asphalt Institute Equation to determine structural fatigue life based on compressive strain is the same for the asphalt concrete layer, the base and the subbase. This equation does not depend on the properties on the layer.

Therefore, the mode of failure resulting from the rupture in compression of the pavement shows a maximum compressive strain of 136.15 microns (*read highest Strain_Z*)

$$N_f = 1.365 * 10^{-9} * (0.13615 * 10^{-3})^{-4,477}$$

$$N_f = 2.8 * 10^{8}$$

The cumulated traffic over 20 years is equal to:

$$Cumulated\ traffic_{20\ years} = 1.1 * 10^{8}\ ESAL$$

$$\frac{N_f}{Cumulated\ traffic_{20\ years}} = \frac{2.8 * 10^{8}}{1.1 * 10^{8}} = 2.6$$

The calculations show a maximum of 280 million repetitions of a 13-ton axle load. Therefore, there is no possibility of a rupture by fatigue before 20 years.

Failure in tension at the bottom of the asphalt concrete

Input Layers

	Thickness	E-Modulus	PR	Slip
1	160.00	3800.0	0.35000	0.0000
2	300.00	2500.0	0.35000	0.0000
3		50.000	0.15000	0.0000
4				
5				
6				

Input Loads

	X-Coord.	Y-Coord.	Load	Contact Area
1	0.0000	0.0000	32500.	38410.
2	0.0000	305.00	32500.	38410.
3				
4				
5				

Input Evaluation Points

	X-Coord.	Y-Coord.
1	0.0000	0.0000
2	0.0000	152.50
3		
4		
5		
6		

Input Calculation Depths

	Depth
1	159.90
2	
3	
4	
5	
6	

Results at Calculations Points

	Point 1	Point 2
X-Coord.	0.0000	0.0000
Y-Coord.	0.0000	152.50
Z-Coord	159.90	159.90
Stress_X	-0.85392E-01	-0.64415E-01
Stress_Y	-0.33785E-01	0.94043E-01
Stress_Z	0.35964	0.26762
ShearStress_XZ	0.0000	0.0000
ShearStress_YZ	-0.28544E-01	0.0000
ShearStress_XY	0.0000	0.0000
Strain_X	-0.52484E-04	-0.50263E-04
Strain_Y	-0.34150E-04	0.60317E-05
Strain_Z	0.10562E-03	0.67698E-04
ShearStrain_XZ	0.0000	0.0000
ShearStrain_YZ	-0.20281E-04	0.0000
ShearStrain_XY	0.0000	0.0000
Displt_X	0.0000	0.0000
Displt_Y	-0.20416E-02	0.0000
Displt_Z	0.43900E-01	0.44072E-01
PrincStress_1	0.36170	0.26762
PrincStress_2	-0.35845E-01	0.94043E-01
PrincStress_3	-0.85392E-01	-0.64415E-01
PrincStrain_1	0.10635E-03	0.67698E-04
PrincStrain_2	-0.34882E-04	0.60317E-05

Figure-A III- 6 12 Tensile strains at the bottom of the asphalt concrete after one 13-ton axle load

WinJulea indicates a maximum for the tensile strain of 52.484 microns *(read max of Strain_X and Strain_Y), as shown Figure-A III- 6 14*

The number of allowable repetitions is calculated with the Asphalt Institute Equation provided below.

The asphalt institute (Asphalt Institute, 1982) suggested that the relationship between fatigue failure of asphalt concrete and tensile strain is represented by the number of load repetitions as follows:

$N_f \quad = \quad 0.0796(\varepsilon_t)^{-3.291}(E)^{-0.854} \quad (8.0)$

Where;

N_f = Number of load applications to failure

ε_t = Horizontal tensile strain at the bottom of asphalt bound layer

E = Elastic Modulus of asphalt concrete

Figure-A III- 6 13 Asphalt Institute Equation to determine structural fatigue life based on tensile strain (Ekwulo and Eme 2009)

$$N_f = 0{,}0796 * (0.52484 * 10^{-4})^{-3{,}291} * (3800 * 10^6 * 0{,}000145038)^{-0.854}$$

$$N_f = 1.2 * 10^8$$

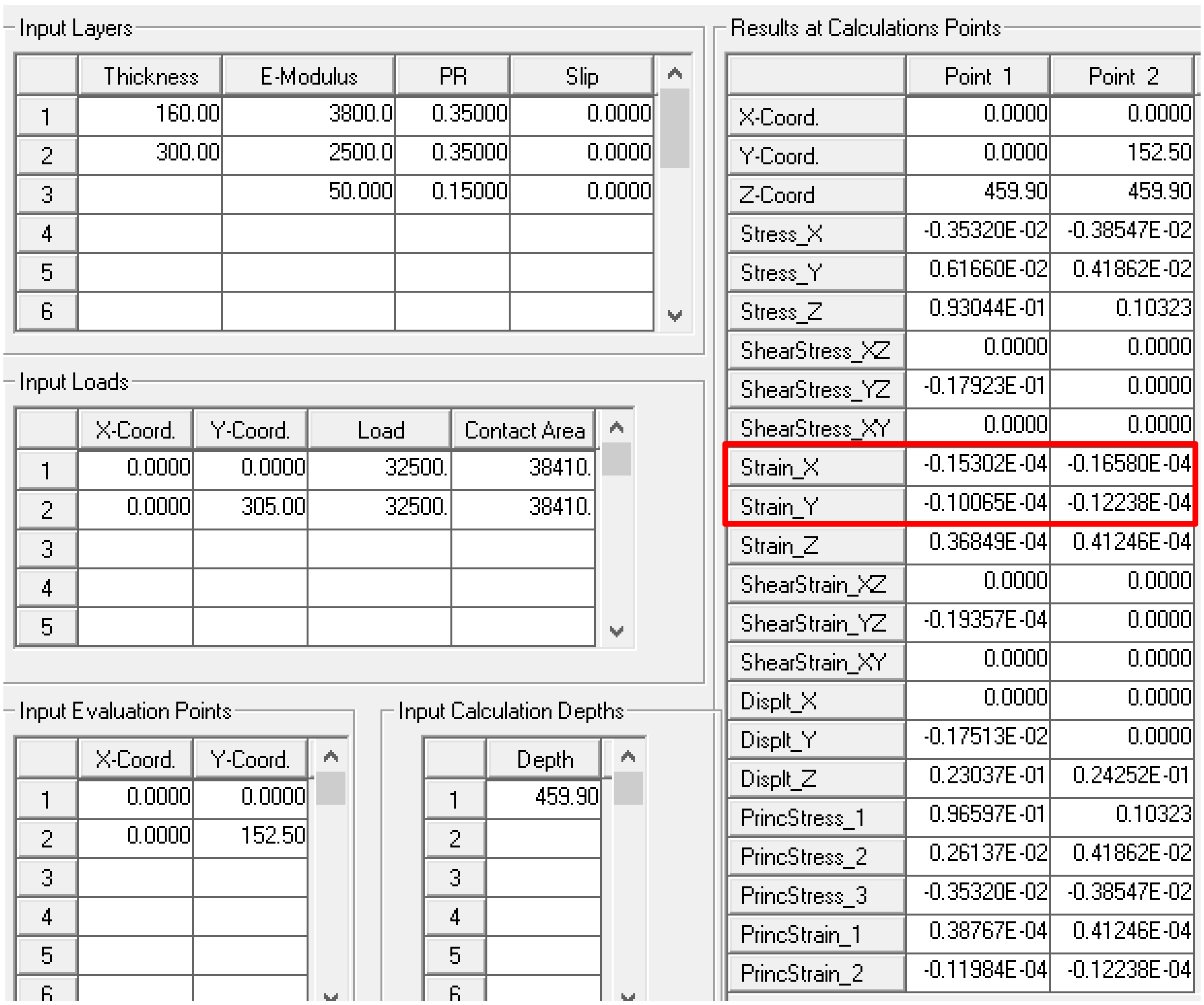
The cumulated traffic over 20 years is equal to:

$$Cumulated\ traffic_{20\ years} = 1.1 * 10^8\ ESAL$$

$$\frac{N_f}{Cumulated\ traffic_{20\ years}} = \frac{1.2 * 10^8}{1.1 * 10^8} = 1.1$$

The calculations show a minimum of 120 million repetitions of a 13-ton axle load. Therefore, there is no possibility of a rupture by fatigue before 20 years.

Failure in tension at the bottom of the base course



Input Layers

	Thickness	E-Modulus	PR	Slip
1	160.00	3800.0	0.35000	0.0000
2	300.00	2500.0	0.35000	0.0000
3		50.000	0.15000	0.0000
4				
5				
6				

Input Loads

	X-Coord.	Y-Coord.	Load	Contact Area
1	0.0000	0.0000	32500.	38410.
2	0.0000	305.00	32500.	38410.
3				
4				
5				

Input Evaluation Points

	X-Coord.	Y-Coord.
1	0.0000	0.0000
2	0.0000	152.50
3		
4		
5		
6		

Input Calculation Depths

	Depth
1	459.90
2	
3	
4	
5	
6	

Results at Calculations Points

	Point 1	Point 2
X-Coord.	0.0000	0.0000
Y-Coord.	0.0000	152.50
Z-Coord	459.90	459.90
Stress_X	-0.35320E-02	-0.38547E-02
Stress_Y	0.61660E-02	0.41862E-02
Stress_Z	0.93044E-01	0.10323
ShearStress_XZ	0.0000	0.0000
ShearStress_YZ	-0.17923E-01	0.0000
ShearStress_XY	0.0000	0.0000
Strain_X	-0.15302E-04	-0.16580E-04
Strain_Y	-0.10065E-04	-0.12238E-04
Strain_Z	0.36849E-04	0.41246E-04
ShearStrain_XZ	0.0000	0.0000
ShearStrain_YZ	-0.19357E-04	0.0000
ShearStrain_XY	0.0000	0.0000
Displt_X	0.0000	0.0000
Displt_Y	-0.17513E-02	0.0000
Displt_Z	0.23037E-01	0.24252E-01
PrincStress_1	0.96597E-01	0.10323
PrincStress_2	0.26137E-02	0.41862E-02
PrincStress_3	-0.35320E-02	-0.38547E-02
PrincStrain_1	0.38767E-04	0.41246E-04
PrincStrain_2	-0.11984E-04	-0.12238E-04

Figure-A III- 6 14 Tensile strains at the bottom of the asphalt concrete after one 13-ton axle load

WinJulea indicates a maximum for the tensile strain of 16.58 microns (read max of Strain_X and Strain_Y*), as shown Figure A III 6-14* in the figure above. The number of allowable repetitions is calculated with the following Asphalt Institute Equation:

$$N_f = 0.0796 * (0.16580 * 10^{-4})^{-3,291} * (2500 * 10^6 * 0.000145038)^{-0.854}$$

$$N_f = 7.7 * 10^9$$

The cumulated traffic over 20 years is equal to:

$$Cumulated\ traffic_{20\ years} = 1.1 * 10^{8}\ ESAL$$

$$\frac{N_f}{Cumulated\ traffic_{20\ years}} = \frac{7.7 * 10^{9}}{1.1 * 10^{8}} = 71$$

The calculations show a minimum of 7.7 billion repetitions of a 13-ton axle load. Therefore, there is no possibility of a rupture by fatigue before 20 years.

ANNEX VII

Assessment of the structural capacity of flexible pavement alternative B, with WinJulea

In order to confirm the structural capacity of the flexible pavement alternative B, a throughout mechanistic analysis is presented below.

Pavement characteristics

The top layer of the structure is a 200-mm conventional asphalt concrete, deploying a modulus of elasticity of 2,500 MPa. The asphalt concrete layer covers a 300-mm cement reclaimed base course, with a modulus of elasticity of 2,500 MPa. The subbase has a weak capacity with an assumed modulus of elasticity of 50 MPa.

Load characteristics

The total weight per ESAL, corresponding to the reference axle, is 13 tons. Therefore, the total weight per tire is equal to 3.25 tons.

The higher **contact pressure** is **830 kPa**. *(refer to sections 2.6.1.2-2.6.1.6).*

Contact area = 384.10 cm^2.

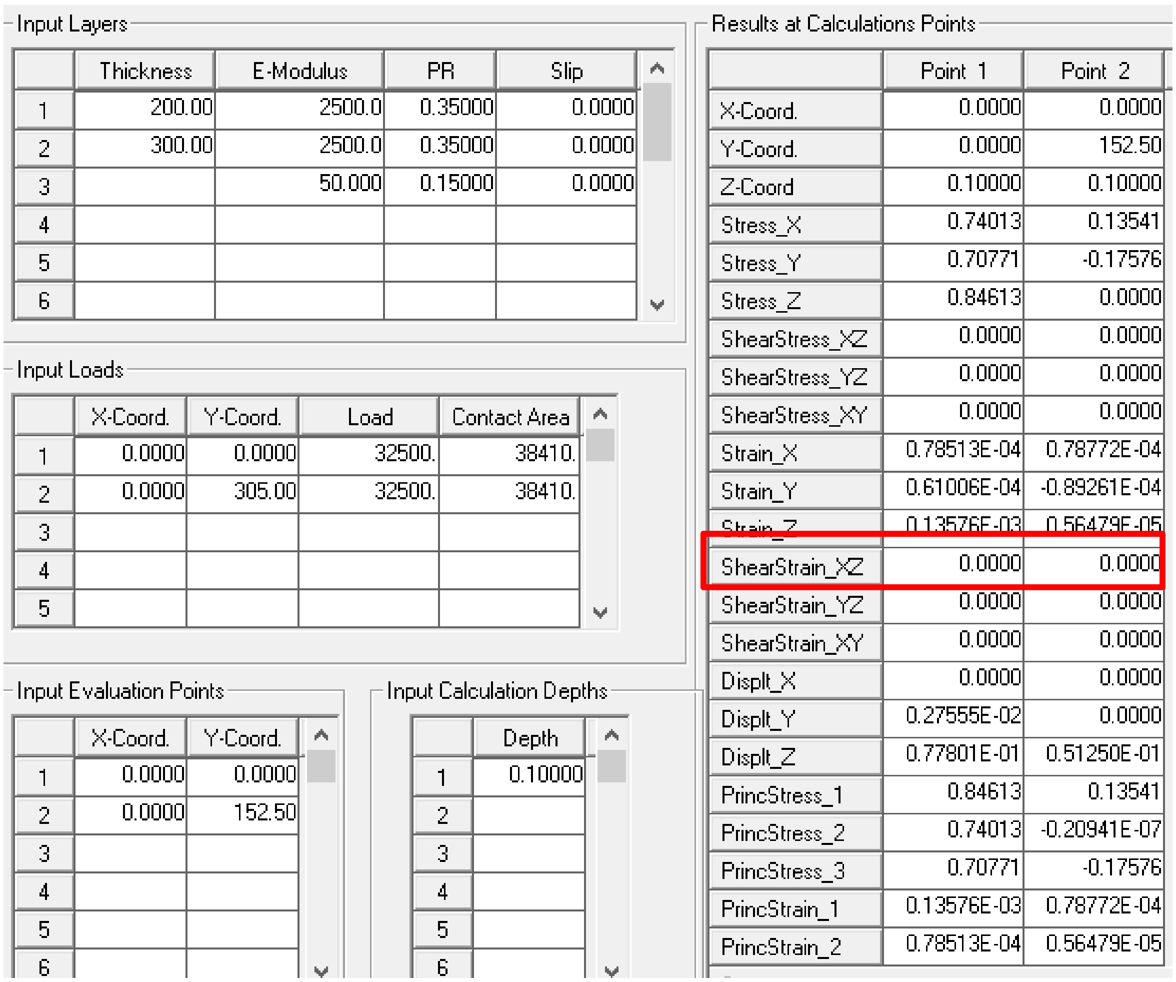
Modes of failure

The structural design of the pavement needs to verify the following modes of failure:

6. Failure in compression at the top of the asphalt concrete;
7. Failure in tension at the bottom of the asphalt concrete;
8. Failure in compression at the top of the base course;
9. Failure in tension at the bottom of the base course; and,
10. Failure in compression at the top of the subbase.

As shown in the following mechanistic analysis, there is no possibility of a rupture by fatigue before 20 years.

Failure in compression at the top of the asphalt concrete



Input Layers

	Thickness	E-Modulus	PR	Slip
1	200.00	2500.0	0.35000	0.0000
2	300.00	2500.0	0.35000	0.0000
3		50.000	0.15000	0.0000
4				
5				
6				

Input Loads

	X-Coord.	Y-Coord.	Load	Contact Area
1	0.0000	0.0000	32500.	38410.
2	0.0000	305.00	32500.	38410.
3				
4				
5				

Input Evaluation Points

	X-Coord.	Y-Coord.
1	0.0000	0.0000
2	0.0000	152.50
3		
4		
5		
6		

Input Calculation Depths

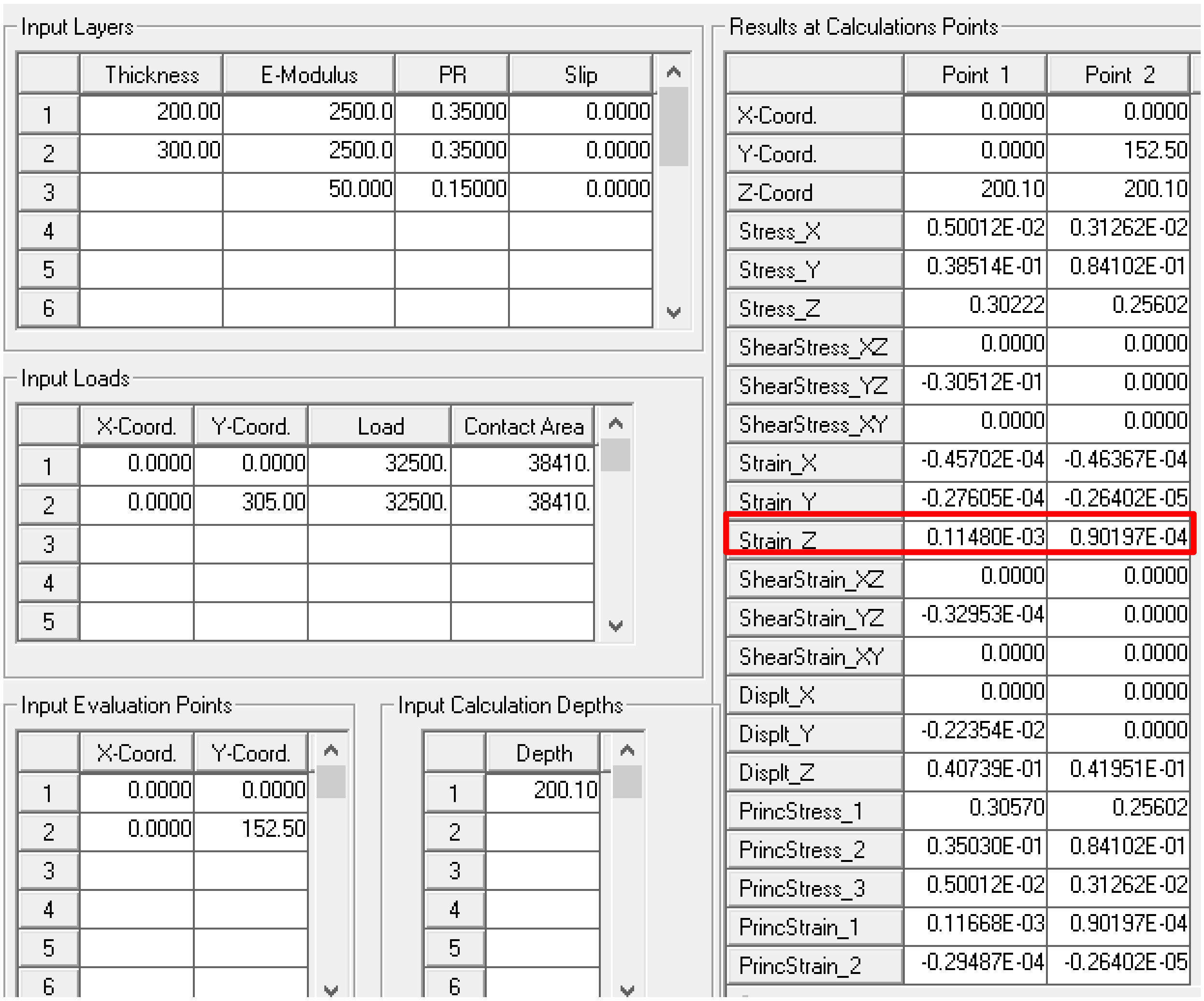
	Depth
1	0.10000
2	
3	
4	
5	
6	

Results at Calculations Points

	Point 1	Point 2
X-Coord.	0.0000	0.0000
Y-Coord.	0.0000	152.50
Z-Coord	0.10000	0.10000
Stress_X	0.74013	0.13541
Stress_Y	0.70771	-0.17576
Stress_Z	0.84613	0.0000
ShearStress_XZ	0.0000	0.0000
ShearStress_YZ	0.0000	0.0000
ShearStress_XY	0.0000	0.0000
Strain_X	0.78513E-04	0.78772E-04
Strain_Y	0.61006E-04	-0.89261E-04
Strain_Z	0.13576E-03	0.56479E-05
ShearStrain_XZ	0.0000	0.0000
ShearStrain_YZ	0.0000	0.0000
ShearStrain_XY	0.0000	0.0000
Displt_X	0.0000	0.0000
Displt_Y	0.27555E-02	0.0000
Displt_Z	0.77801E-01	0.51250E-01
PrincStress_1	0.84613	0.13541
PrincStress_2	0.74013	-0.20941E-07
PrincStress_3	0.70771	-0.17576
PrincStrain_1	0.13576E-03	0.78772E-04
PrincStrain_2	0.78513E-04	0.56479E-05

Figure-A III- 6 15 Compressive strain at the top of the asphalt concrete after one 13-ton axle load

Failure in compression at the top of the base course



Input Layers

	Thickness	E-Modulus	PR	Slip
1	200.00	2500.0	0.35000	0.0000
2	300.00	2500.0	0.35000	0.0000
3		50.000	0.15000	0.0000
4				
5				
6				

Input Loads

	X-Coord.	Y-Coord.	Load	Contact Area
1	0.0000	0.0000	32500.	38410.
2	0.0000	305.00	32500.	38410.
3				
4				
5				

Input Evaluation Points

	X-Coord.	Y-Coord.
1	0.0000	0.0000
2	0.0000	152.50
3		
4		
5		
6		

Input Calculation Depths

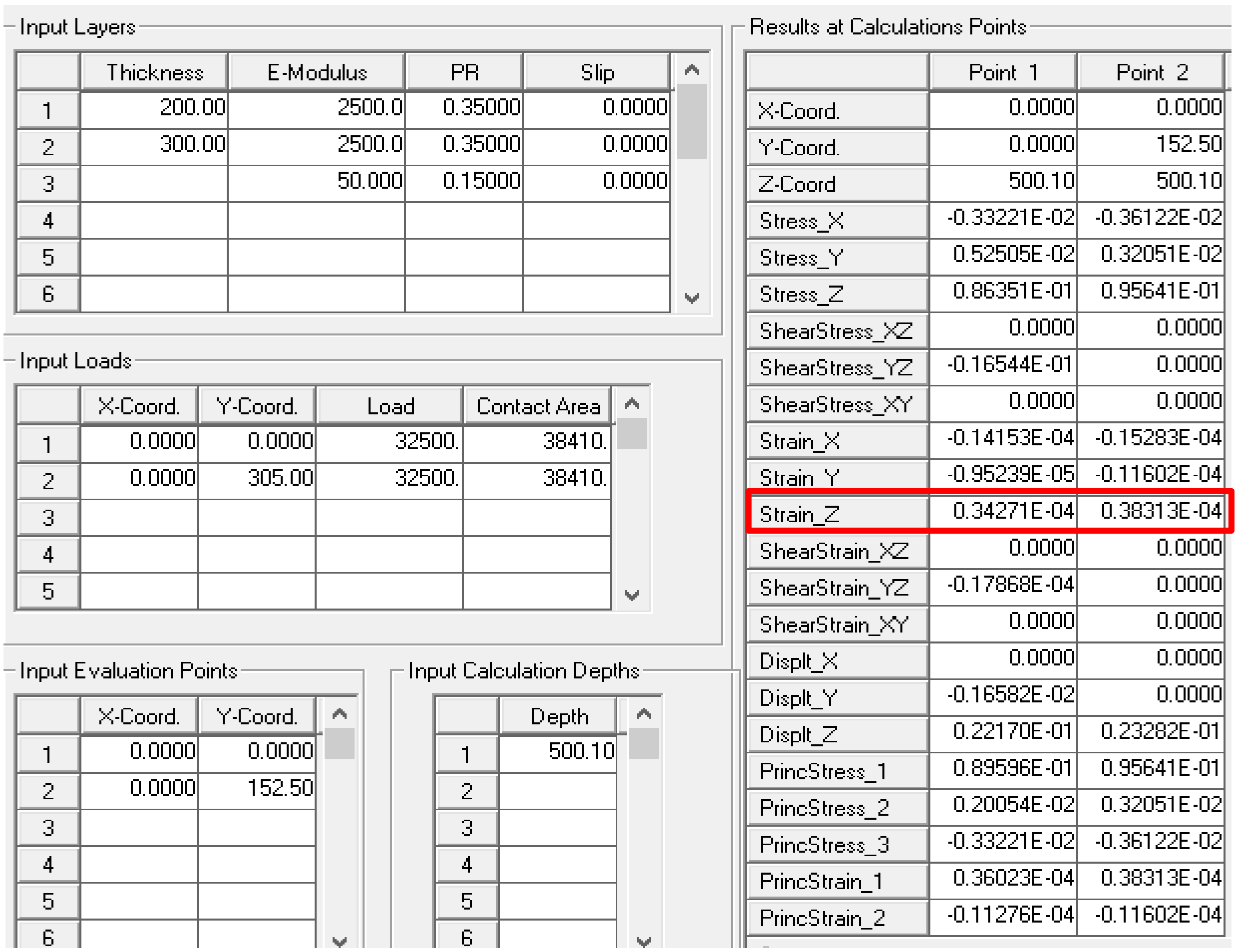
	Depth
1	200.10
2	
3	
4	
5	
6	

Results at Calculations Points

	Point 1	Point 2
X-Coord.	0.0000	0.0000
Y-Coord.	0.0000	152.50
Z-Coord	200.10	200.10
Stress_X	0.50012E-02	0.31262E-02
Stress_Y	0.38514E-01	0.84102E-01
Stress_Z	0.30222	0.25602
ShearStress_XZ	0.0000	0.0000
ShearStress_YZ	-0.30512E-01	0.0000
ShearStress_XY	0.0000	0.0000
Strain_X	-0.45702E-04	-0.46367E-04
Strain_Y	-0.27605E-04	-0.26402E-05
Strain_Z	0.11480E-03	0.90197E-04
ShearStrain_XZ	0.0000	0.0000
ShearStrain_YZ	-0.32953E-04	0.0000
ShearStrain_XY	0.0000	0.0000
Displt_X	0.0000	0.0000
Displt_Y	-0.22354E-02	0.0000
Displt_Z	0.40739E-01	0.41951E-01
PrincStress_1	0.30570	0.25602
PrincStress_2	0.35030E-01	0.84102E-01
PrincStress_3	0.50012E-02	0.31262E-02
PrincStrain_1	0.11668E-03	0.90197E-04
PrincStrain_2	-0.29487E-04	-0.26402E-05

Figure-A III- 6 16 Compressive strains at the top of the base course after one 13-ton axle load

Failure in compression at the top of the subbase



Input Layers

	Thickness	E-Modulus	PR	Slip
1	200.00	2500.0	0.35000	0.0000
2	300.00	2500.0	0.35000	0.0000
3		50.000	0.15000	0.0000
4				
5				
6				

Input Loads

	X-Coord.	Y-Coord.	Load	Contact Area
1	0.0000	0.0000	32500.	38410.
2	0.0000	305.00	32500.	38410.
3				
4				
5				

Input Evaluation Points

	X-Coord.	Y-Coord.
1	0.0000	0.0000
2	0.0000	152.50
3		
4		
5		
6		

Input Calculation Depths

	Depth
1	500.10
2	
3	
4	
5	
6	

Results at Calculations Points

	Point 1	Point 2
X-Coord.	0.0000	0.0000
Y-Coord.	0.0000	152.50
Z-Coord	500.10	500.10
Stress_X	-0.33221E-02	-0.36122E-02
Stress_Y	0.52505E-02	0.32051E-02
Stress_Z	0.86351E-01	0.95641E-01
ShearStress_XZ	0.0000	0.0000
ShearStress_YZ	-0.16544E-01	0.0000
ShearStress_XY	0.0000	0.0000
Strain_X	-0.14153E-04	-0.15283E-04
Strain_Y	-0.95239E-05	-0.11602E-04
Strain_Z	0.34271E-04	0.38313E-04
ShearStrain_XZ	0.0000	0.0000
ShearStrain_YZ	-0.17868E-04	0.0000
ShearStrain_XY	0.0000	0.0000
Displt_X	0.0000	0.0000
Displt_Y	-0.16582E-02	0.0000
Displt_Z	0.22170E-01	0.23282E-01
PrincStress_1	0.89596E-01	0.95641E-01
PrincStress_2	0.20054E-02	0.32051E-02
PrincStress_3	-0.33221E-02	-0.36122E-02
PrincStrain_1	0.36023E-04	0.38313E-04
PrincStrain_2	-0.11276E-04	-0.11602E-04

Figure-A III- 6 17 Compressive strains at the top of the subbase after one 13-ton axle load

Allowable number of repetitions to prevent compression failure of the subgrade is calculated with the equation provided below:

$$N_f = 1.365 x 10^{-9} (\varepsilon_c)^{-4.477} \quad (11.0)$$

Where;

N_f = Number of load applications to failure

ε_c = Vertical Compressive strain at the bottom of asphalt bound layer

Figure-A III- 6 18 Asphalt Institute Equation to determine structural fatigue life based on compressive strain (Ekwulo and Eme 2009)

We assume that the Asphalt Institute Equation to determine structural fatigue life based on compressive strain is the same for the asphalt concrete layer, the base and the subbase. This equation does not depend on the properties on the layer *(as the modulus of elasticity, for the Asphalt Institute Equation to determine structural fatigue life based on tensile strain).*

Therefore, the mode of failure resulting from the rupture in compression of the pavement shows a maximum compressive strain of 220.31 microns (*read highest Strain_Z*), *as shown in the figure below.*

$$N_f = 1.365 * 10^{-9} * (0.13576 * 10^{-3})^{-4,477}$$

$$N_f = 2.8 * 10^8$$

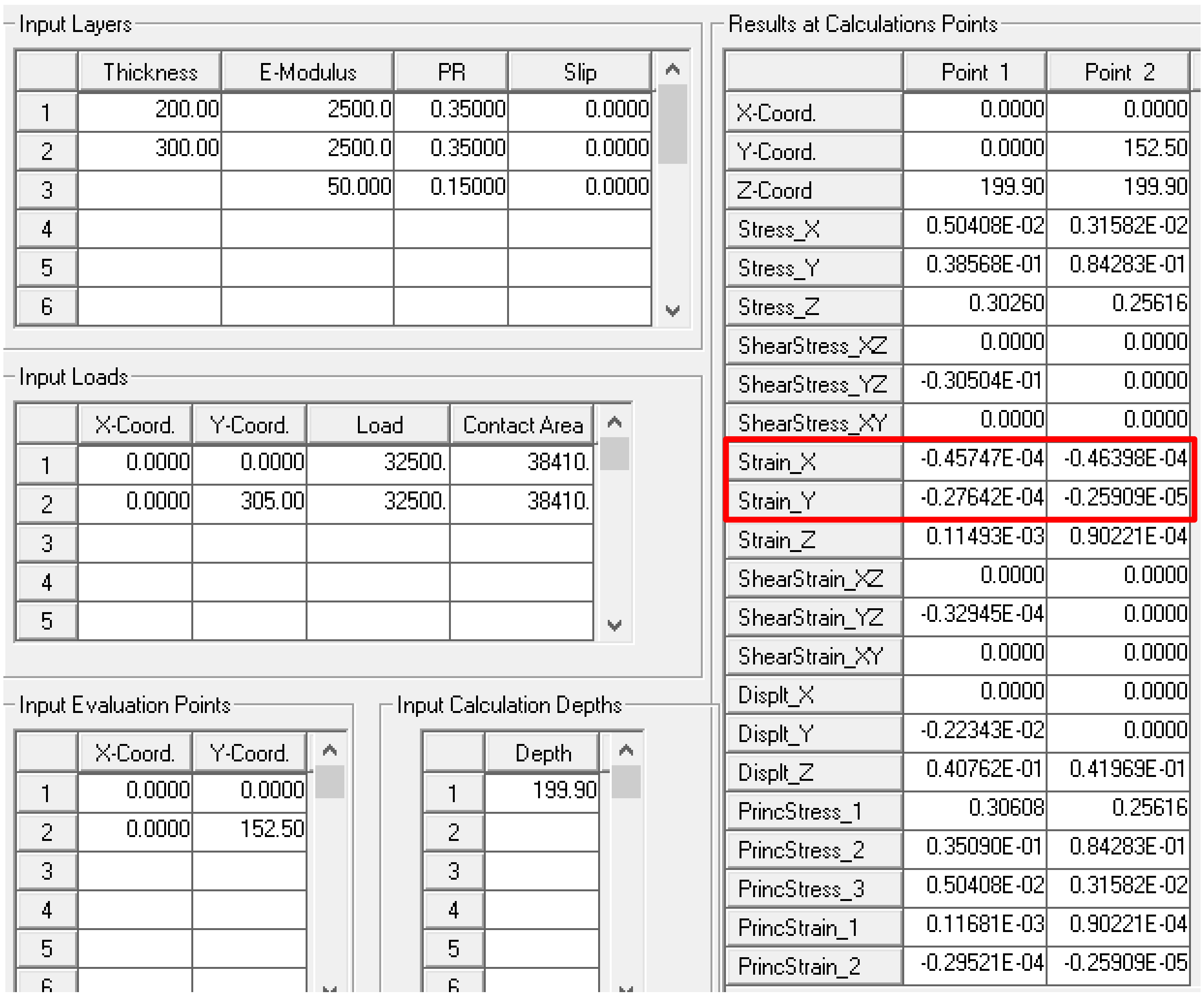
The cumulated traffic over 20 years is equal to:

$$Cumulated\ traffic_{20\ years} = 1.1 * 10^8\ ESAL$$

$$\frac{N_f}{Cumulated\ traffic_{20\ years}} = \frac{2.8 * 10^8}{1.1 * 10^8} = 2.5$$

The calculations show a maximum of 280 million repetitions of a 13-ton axle load. Therefore, there is no possibility of a rupture by fatigue before 20 years.

Failure in tension at the bottom of the asphalt concrete



Input Layers

	Thickness	E-Modulus	PR	Slip
1	200.00	2500.0	0.35000	0.0000
2	300.00	2500.0	0.35000	0.0000
3		50.000	0.15000	0.0000
4				
5				
6				

Input Loads

	X-Coord.	Y-Coord.	Load	Contact Area
1	0.0000	0.0000	32500.	38410.
2	0.0000	305.00	32500.	38410.
3				
4				
5				

Input Evaluation Points

	X-Coord.	Y-Coord.
1	0.0000	0.0000
2	0.0000	152.50
3		
4		
5		
6		

Input Calculation Depths

	Depth
1	199.90
2	
3	
4	
5	
6	

Results at Calculations Points

	Point 1	Point 2
X-Coord.	0.0000	0.0000
Y-Coord.	0.0000	152.50
Z-Coord	199.90	199.90
Stress_X	0.50408E-02	0.31582E-02
Stress_Y	0.38568E-01	0.84283E-01
Stress_Z	0.30260	0.25616
ShearStress_XZ	0.0000	0.0000
ShearStress_YZ	-0.30504E-01	0.0000
ShearStress_XY	0.0000	0.0000
Strain_X	-0.45747E-04	-0.46398E-04
Strain_Y	-0.27642E-04	-0.25909E-05
Strain_Z	0.11493E-03	0.90221E-04
ShearStrain_XZ	0.0000	0.0000
ShearStrain_YZ	-0.32945E-04	0.0000
ShearStrain_XY	0.0000	0.0000
Displt_X	0.0000	0.0000
Displt_Y	-0.22343E-02	0.0000
Displt_Z	0.40762E-01	0.41969E-01
PrincStress_1	0.30608	0.25616
PrincStress_2	0.35090E-01	0.84283E-01
PrincStress_3	0.50408E-02	0.31582E-02
PrincStrain_1	0.11681E-03	0.90221E-04
PrincStrain_2	-0.29521E-04	-0.25909E-05

Figure-A III- 6 19 Tensile strains at the bottom of the asphalt concrete after one 13-ton axle load

WinJulea indicates a maximum for the tensile strain of 76.645 microns *(read max of Strain_X and Strain_Y), as shown in the figure above*.

The number of allowable repetitions is calculated with the Asphalt Institute Equation provided below:

.

The asphalt institute (Asphalt Institute, 1982) suggested that the relationship between fatigue failure of asphalt concrete and tensile strain is represented by the number of load repetitions as follows:

$$N_f = 0.0796(\varepsilon_t)^{-3.291}(E)^{-0.854} \qquad (8.0)$$

Where;

N_f = Number of load applications to failure

ε_t = Horizontal tensile strain at the bottom of asphalt bound layer

E = Elastic Modulus of asphalt concrete

Figure-A III- 6 20 Asphalt Institute Equation to determine structural fatigue life based on tensile strain (Ekwulo and Eme 2009)

$$N_f = 0{,}0796 * (0.46389 * 10^{-4})^{-3{,}291} * (2500 * 10^6 * 0{,}000145038)^{-0.854}$$

$$N_f = 2.6 * 10^8$$

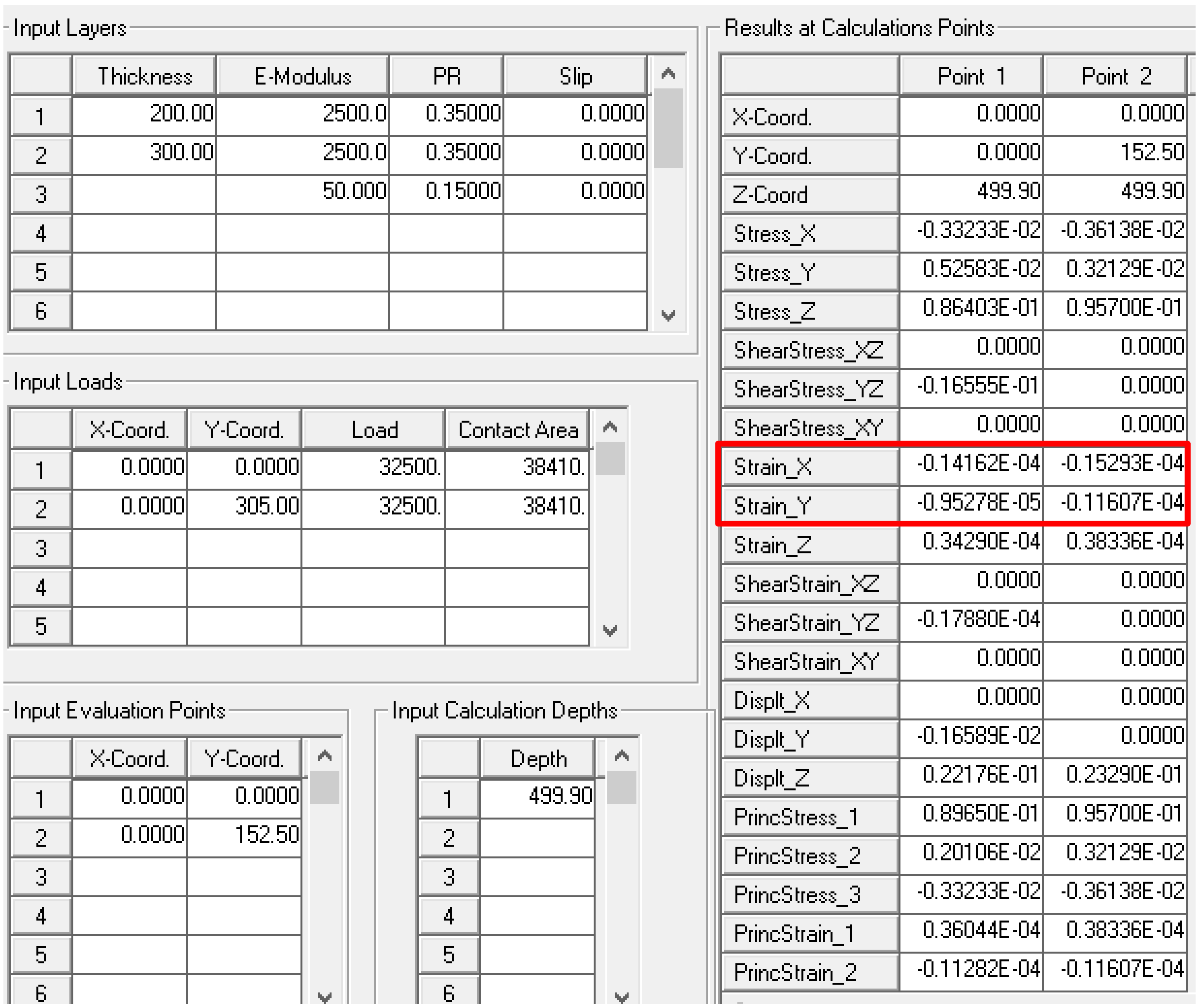
The cumulated traffic over 20 years is equal to:

$$Cumulated\ traffic_{20\ years} = 1.1 * 10^8\ ESAL$$

$$\frac{N_f}{Cumulated\ traffic_{20\ years}} = \frac{2.6 * 10^8}{1.1 * 10^8} = 2.4$$

The calculations show a minimum of 260 million repetitions of a 13-ton axle load. Therefore, there is no possibility of a rupture by fatigue before 20 years.

Failure in tension at the bottom of the base course



Input Layers

	Thickness	E-Modulus	PR	Slip
1	200.00	2500.0	0.35000	0.0000
2	300.00	2500.0	0.35000	0.0000
3		50.000	0.15000	0.0000
4				
5				
6				

Input Loads

	X-Coord.	Y-Coord.	Load	Contact Area
1	0.0000	0.0000	32500.	38410.
2	0.0000	305.00	32500.	38410.
3				
4				
5				

Input Evaluation Points

	X-Coord.	Y-Coord.
1	0.0000	0.0000
2	0.0000	152.50
3		
4		
5		
6		

Input Calculation Depths

	Depth
1	499.90
2	
3	
4	
5	
6	

Results at Calculations Points

	Point 1	Point 2
X-Coord.	0.0000	0.0000
Y-Coord.	0.0000	152.50
Z-Coord	499.90	499.90
Stress_X	-0.33233E-02	-0.36138E-02
Stress_Y	0.52583E-02	0.32129E-02
Stress_Z	0.86403E-01	0.95700E-01
ShearStress_XZ	0.0000	0.0000
ShearStress_YZ	-0.16555E-01	0.0000
ShearStress_XY	0.0000	0.0000
Strain_X	-0.14162E-04	-0.15293E-04
Strain_Y	-0.95278E-05	-0.11607E-04
Strain_Z	0.34290E-04	0.38336E-04
ShearStrain_XZ	0.0000	0.0000
ShearStrain_YZ	-0.17880E-04	0.0000
ShearStrain_XY	0.0000	0.0000
Displt_X	0.0000	0.0000
Displt_Y	-0.16589E-02	0.0000
Displt_Z	0.22176E-01	0.23290E-01
PrincStress_1	0.89650E-01	0.95700E-01
PrincStress_2	0.20106E-02	0.32129E-02
PrincStress_3	-0.33233E-02	-0.36138E-02
PrincStrain_1	0.36044E-04	0.38336E-04
PrincStrain_2	-0.11282E-04	-0.11607E-04

Figure-A III- 6 21 Tensile strains at the bottom of the asphalt concrete after one 13-ton axle load

WinJulea indicates a maximum for the tensile strain of 15.293 microns (read max of Strain_X and Strain_Y*), as shown figure A III- 6-21.* The number of allowable repetitions is calculated with the Asphalt Institute Equation *below:*

$$N_f = 0.0796 * (0.15293 * 10^{-4})^{-3,291} * (2500 * 10^{6} * 0.000145038)^{-0.854}$$

$$N_f = 10^{10}$$

The cumulated traffic over 20 years is equal to:

$$Cumulated\ traffic_{20\ years} = 1.1 * 10^{8}\ ESAL$$

$$\frac{N_f}{Cumulated\ traffic_{20\ years}} = \frac{10^{10}}{1.1 * 10^{8}} = 91$$

The calculations show a minimum of 10 billion repetitions of a 13-ton axle load. Therefore, there is no possibility of a rupture by fatigue before 20 years.

ANNEX VIII

Assessment of the structural capacity of flexible pavement alternative C, with WinJulea

In order to confirm the structural capacity of the flexible pavement alternative A, a throughout mechanistic analysis is presented below.

Pavement characteristics

The top layer of the structure is a 100-mm high-modulus polymer-modified asphalt concrete (AC) with fiber, deploying a modulus of elasticity of 3,800 MPa. The asphalt concrete layer covers a 300-mm cement reclaimed base course, with a modulus of elasticity of 2,500 MPa. The subbase has a weak capacity with an assumed modulus of elasticity of 50 MPa.

Load characteristics

The total weight per ESAL, *corresponding to the reference axle in the EGIS report*, is 13 tons. Therefore, the total weight per tire is equal to 3.25 tons.

The higher **contact pressure** is **830 kPa**. *(refer to sections 2.6.1.2-2.6.1.6).*

Contact area = 384.10 cm^2*)*.

Modes of failure

The structural design of the pavement needs to verify the following modes of failure:

11. Failure in compression at the top of the asphalt concrete;
12. Failure in tension at the bottom of the asphalt concrete;
13. Failure in compression at the top of the base course;
14. Failure in tension at the bottom of the base course; and,
15. Failure in compression at the top of the subbase.

As shown in the following mechanistic analysis, there is no possibility of a rupture by fatigue before 20 years.

Failure in compression at the top of the asphalt concrete

Input Layers

	Thickness	E-Modulus	PR	Slip
1	100.00	3800.0	0.35000	0.0000
2	300.00	2500.0	0.35000	0.0000
3		50.000	0.15000	0.0000
4				
5				
6				

Input Loads

	X-Coord.	Y-Coord.	Load	Contact Area
1	0.0000	0.0000	32500.	38410.
2	0.0000	305.00	32500.	38410.
3				
4				
5				

Input Evaluation Points

	X-Coord.	Y-Coord.
1	0.0000	0.0000
2	0.0000	152.20
3		
4		
5		
6		

Input Calculation Depths

	Depth
1	0.10000
2	
3	
4	
5	
6	

Results at Calculations Points

	Point 1	Point 2
X-Coord.	0.0000	0.0000
Y-Coord.	0.0000	152.20
Z-Coord	0.10000	0.10000
Stress_X	0.85693	0.25410
Stress_Y	0.80460	-0.25008
Stress_Z	0.84613	0.0000
ShearStress_XZ	0.0000	0.0000
ShearStress_YZ	0.0000	0.0000
ShearStress_XY	0.0000	0.0000
Strain_X	0.73467E-04	0.89903E-04
Strain_Y	0.54876E-04	-0.89215E-04
Strain_Z	0.69631E-04	-0.37060E-06
ShearStrain_XZ	0.0000	0.0000
ShearStrain_YZ	0.0000	0.0000
ShearStrain_XY	0.0000	0.0000
Displt_X	0.0000	0.0000
Displt_Y	0.27416E-02	-0.31879E-04
Displt_Z	0.68020E-01	0.50780E-01
PrincStress_1	0.85693	0.25410
PrincStress_2	0.84613	-0.33931E-07
PrincStress_3	0.80460	-0.25008
PrincStrain_1	0.73467E-04	0.89903E-04
PrincStrain_2	0.69631E-04	-0.37061E-06

Figure-A III- 6 22 Compressive strains at the top of the asphalt concrete after one 13-ton axle load

Failure in compression at the top of the base course

Input Layers

	Thickness	E-Modulus	PR	Slip
1	100.00	3800.0	0.35000	0.0000
2	300.00	2500.0	0.35000	0.0000
3		50.000	0.15000	0.0000
4				
5				
6				

Input Loads

	X-Coord.	Y-Coord.	Load	Contact Area
1	0.0000	0.0000	32500.	38410.
2	0.0000	305.00	32500.	38410.
3				
4				
5				

Input Evaluation Points

	X-Coord.	Y-Coord.
1	0.0000	0.0000
2	0.0000	152.20
3		
4		
5		
6		

Input Calculation Depths

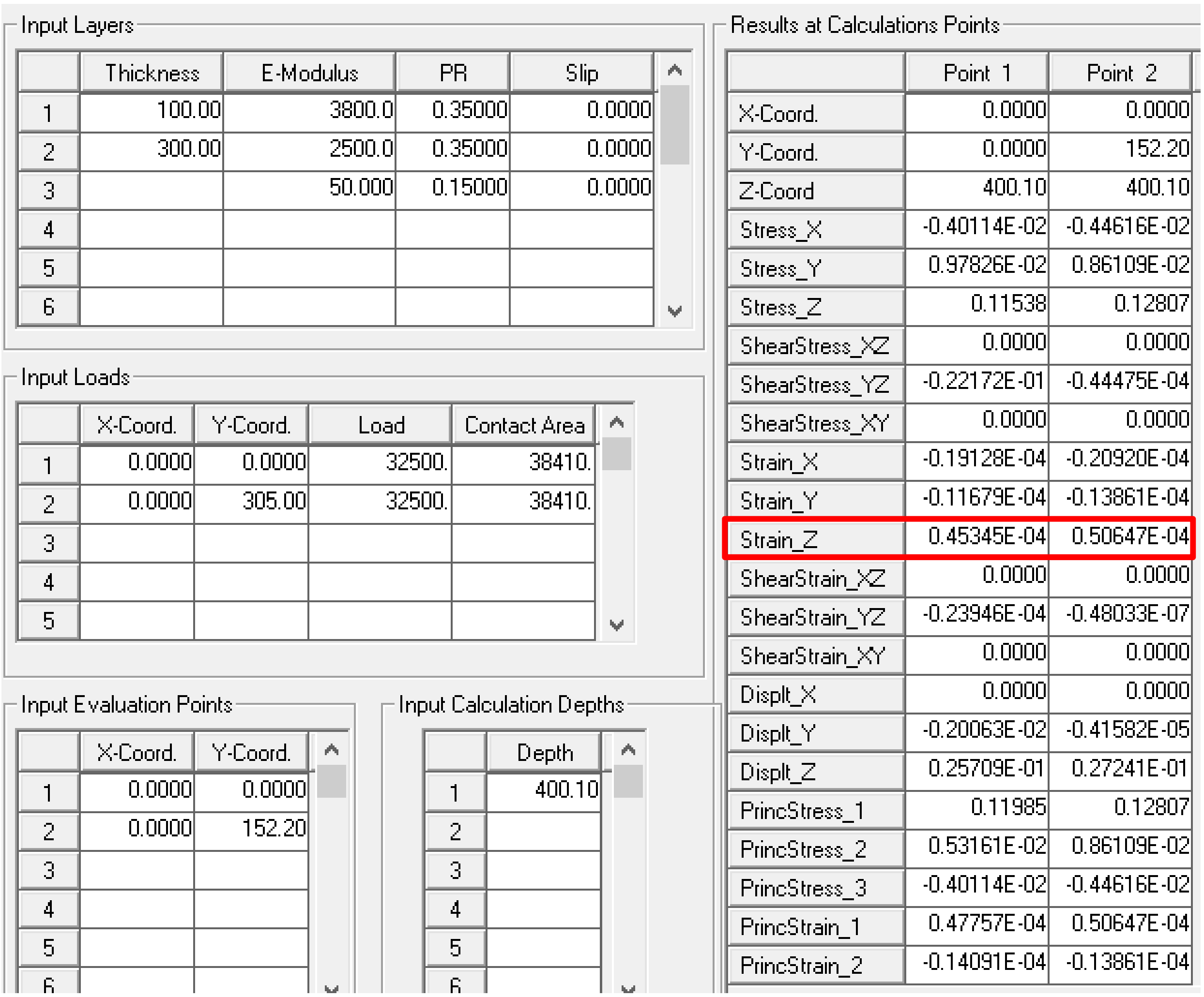
	Depth
1	100.10
2	
3	
4	
5	
6	

Results at Calculations Points

	Point 1	Point 2
X-Coord.	0.0000	0.0000
Y-Coord.	0.0000	152.20
Z-Coord	100.10	100.10
Stress_X	0.69503E-01	0.37203E-01
Stress_Y	0.97149E-01	0.20794
Stress_Z	0.55369	0.28564
ShearStress_XZ	0.0000	0.0000
ShearStress_YZ	-0.18965E-01	0.58397E-03
ShearStress_XY	0.0000	0.0000
Strain_X	-0.63316E-04	-0.54219E-04
Strain_Y	-0.48387E-04	0.37977E-04
Strain_Z	0.19814E-03	0.79935E-04
ShearStrain_XZ	0.0000	0.0000
ShearStrain_YZ	-0.20482E-04	0.63069E-06
ShearStrain_XY	0.0000	0.0000
Displt_X	0.0000	0.0000
Displt_Y	-0.10412E-02	0.11393E-04
Displt_Z	0.54504E-01	0.50055E-01
PrincStress_1	0.55447	0.28564
PrincStress_2	0.96363E-01	0.20793
PrincStress_3	0.69503E-01	0.37203E-01
PrincStrain_1	0.19857E-03	0.79938E-04
PrincStrain_2	-0.48811E-04	0.37974E-04

Figure-A III- 6 23 Compressive strains at the top of the base course after one 13-ton axle load

Failure in compression at the top of the subbase



Input Layers

	Thickness	E-Modulus	PR	Slip
1	100.00	3800.0	0.35000	0.0000
2	300.00	2500.0	0.35000	0.0000
3		50.000	0.15000	0.0000
4				
5				
6				

Input Loads

	X-Coord.	Y-Coord.	Load	Contact Area
1	0.0000	0.0000	32500.	38410.
2	0.0000	305.00	32500.	38410.
3				
4				
5				

Input Evaluation Points

	X-Coord.	Y-Coord.
1	0.0000	0.0000
2	0.0000	152.20
3		
4		
5		
6		

Input Calculation Depths

	Depth
1	400.10
2	
3	
4	
5	
6	

Results at Calculations Points

	Point 1	Point 2
X-Coord.	0.0000	0.0000
Y-Coord.	0.0000	152.20
Z-Coord	400.10	400.10
Stress_X	-0.40114E-02	-0.44616E-02
Stress_Y	0.97826E-02	0.86109E-02
Stress_Z	0.11538	0.12807
ShearStress_XZ	0.0000	0.0000
ShearStress_YZ	-0.22172E-01	-0.44475E-04
ShearStress_XY	0.0000	0.0000
Strain_X	-0.19128E-04	-0.20920E-04
Strain_Y	-0.11679E-04	-0.13861E-04
Strain_Z	0.45345E-04	0.50647E-04
ShearStrain_XZ	0.0000	0.0000
ShearStrain_YZ	-0.23946E-04	-0.48033E-07
ShearStrain_XY	0.0000	0.0000
Displt_X	0.0000	0.0000
Displt_Y	-0.20063E-02	-0.41582E-05
Displt_Z	0.25709E-01	0.27241E-01
PrincStress_1	0.11985	0.12807
PrincStress_2	0.53161E-02	0.86109E-02
PrincStress_3	-0.40114E-02	-0.44616E-02
PrincStrain_1	0.47757E-04	0.50647E-04
PrincStrain_2	-0.14091E-04	-0.13861E-04

Figure-A III- 6 24 Compressive strains at the top of the subbase after one 13-ton axle load

Allowable number of repetitions to prevent compression failure of the subgrade is calculated with the equation provided below:

$$N_f = 1.365\,x10^{-9}\left(\varepsilon_c\right)^{-4.477} \qquad (11.0)$$

Where;
N_f = Number of load applications to failure
ε_c = Vertical Compressive strain at the bottom of asphalt bound layer

Figure-A III- 6 25 Asphalt Institute Equation to determine structural fatigue life based on compressive strain (Ekwulo and Eme 2009)

We assume that the Asphalt Institute Equation to determine structural fatigue life based on compressive strain is the same for the asphalt concrete layer, the base and the subbase. This equation does not depend on the properties on the layer.

Therefore, the mode of failure resulting from the rupture in compression of the pavement shows a maximum compressive strain of 198.14 microns

$$N_f = 1.365 * 10^{-9} * \ (0.19814 * 10^{-3})^{-4,477}$$

$$N_f = 5.9 * 10^{7}$$

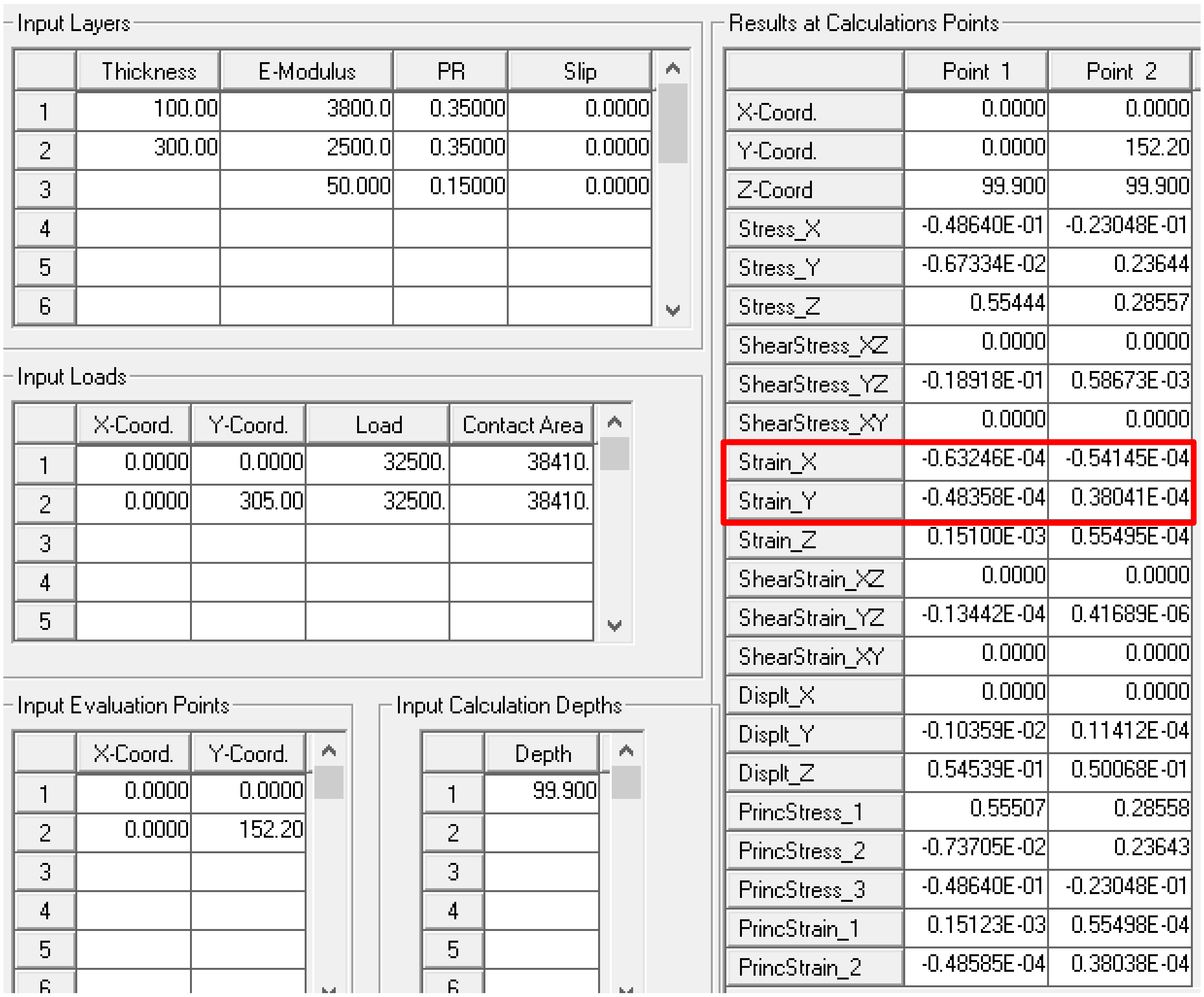
The cumulated traffic over 20 years is equal to:

$$Cumulated\ traffic_{20\ years} = \ 4.5 * 10^{7}\ ESAL$$

$$\frac{N_f}{Cumulated\ traffic_{20\ years}} = \frac{5.9 * 10^{7}}{4.5 * 10^{7}} = 1.3$$

The calculations show a maximum of 59 million repetitions of a 13-ton axle load. Therefore, there is no possibility of a rupture by fatigue before 20 years.

Failure in tension at the bottom of the asphalt concrete



Input Layers

	Thickness	E-Modulus	PR	Slip
1	100.00	3800.0	0.35000	0.0000
2	300.00	2500.0	0.35000	0.0000
3		50.000	0.15000	0.0000
4				
5				
6				

Input Loads

	X-Coord.	Y-Coord.	Load	Contact Area
1	0.0000	0.0000	32500.	38410.
2	0.0000	305.00	32500.	38410.
3				
4				
5				

Input Evaluation Points

	X-Coord.	Y-Coord.
1	0.0000	0.0000
2	0.0000	152.20
3		
4		
5		
6		

Input Calculation Depths

	Depth
1	99.900
2	
3	
4	
5	
6	

Results at Calculations Points

	Point 1	Point 2
X-Coord.	0.0000	0.0000
Y-Coord.	0.0000	152.20
Z-Coord	99.900	99.900
Stress_X	-0.48640E-01	-0.23048E-01
Stress_Y	-0.67334E-02	0.23644
Stress_Z	0.55444	0.28557
ShearStress_XZ	0.0000	0.0000
ShearStress_YZ	-0.18918E-01	0.58673E-03
ShearStress_XY	0.0000	0.0000
Strain_X	-0.63246E-04	-0.54145E-04
Strain_Y	-0.48358E-04	0.38041E-04
Strain_Z	0.15100E-03	0.55495E-04
ShearStrain_XZ	0.0000	0.0000
ShearStrain_YZ	-0.13442E-04	0.41689E-06
ShearStrain_XY	0.0000	0.0000
Displt_X	0.0000	0.0000
Displt_Y	-0.10359E-02	0.11412E-04
Displt_Z	0.54539E-01	0.50068E-01
PrincStress_1	0.55507	0.28558
PrincStress_2	-0.73705E-02	0.23643
PrincStress_3	-0.48640E-01	-0.23048E-01
PrincStrain_1	0.15123E-03	0.55498E-04
PrincStrain_2	-0.48585E-04	0.38038E-04

Figure-A III- 6 26 Tensile strains at the bottom of the asphalt concrete after one 13-ton axle load

WinJulea indicates a maximum for the tensile strain of 63.246 microns *(read max of Strain_X and Strain_Y), as shown Figure above.*

The number of allowable repetitions is calculated with the Asphalt Institute Equation provided below:

The asphalt institute (Asphalt Institute, 1982) suggested that the relationship between fatigue failure of asphalt concrete and tensile strain is represented by the number of load repetitions as follows:

$$N_f = 0.0796(\varepsilon_t)^{-3.291}(E)^{-0.854} \quad (8.0)$$

Where;

N_f = Number of load applications to failure

ε_t = Horizontal tensile strain at the bottom of asphalt bound layer

E = Elastic Modulus of asphalt concrete

Figure-A III- 6 27 Asphalt Institute Equation to determine structural fatigue life based on tensile strain (Ekwulo and Eme 2009)

$$N_f = 0{,}0796 * (0.63246 * 10^{-4})^{-3{,}291} * (3800 * 10^{6} * 0{,}000145038)^{-0.854}$$

$$N_f = 6.6 * 10^{7}$$

The cumulated traffic over 20 years is equal to:

$$Cumulated\ traffic_{20\ years} = 4.5 * 10^{7}\ ESAL$$

$$\frac{N_f}{Cumulated\ traffic_{20\ years}} = \frac{6.6 * 10^{7}}{4.5 * 10^{7}} = 1.5$$

The calculations show a minimum of 66 million repetitions of a 13-ton axle load. Therefore, there is no possibility of a rupture by fatigue before 20 years. For reference ANNEX VIII was obtained from (WSP 2020a)

Failure in tension at the bottom of the base course

Input Layers

	Thickness	E-Modulus	PR	Slip
1	100.00	3800.0	0.35000	0.0000
2	300.00	2500.0	0.35000	0.0000
3		50.000	0.15000	0.0000
4				
5				
6				

Input Loads

	X-Coord.	Y-Coord.	Load	Contact Area
1	0.0000	0.0000	32500.	38410.
2	0.0000	305.00	32500.	38410.
3				
4				
5				

Input Evaluation Points

	X-Coord.	Y-Coord.
1	0.0000	0.0000
2	0.0000	152.20
3		
4		
5		
6		

Input Calculation Depths

	Depth
1	399.90
2	
3	
4	
5	
6	

Results at Calculations Points

	Point 1	Point 2
X-Coord.	0.0000	0.0000
Y-Coord.	0.0000	152.20
Z-Coord	399.90	399.90
Stress_X	-0.40122E-02	-0.44629E-02
Stress_Y	0.97964E-02	0.86300E-02
Stress_Z	0.11546	0.12815
ShearStress_XZ	0.0000	0.0000
ShearStress_YZ	-0.22185E-01	-0.44490E-04
ShearStress_XY	0.0000	0.0000
Strain_X	-0.19141E-04	-0.20935E-04
Strain_Y	-0.11685E-04	-0.13865E-04
Strain_Z	0.45376E-04	0.50679E-04
ShearStrain_XZ	0.0000	0.0000
ShearStrain_YZ	-0.23960E-04	-0.48049E-07
ShearStrain_XY	0.0000	0.0000
Displt_X	0.0000	0.0000
Displt_Y	-0.20070E-02	-0.41595E-05
Displt_Z	0.25718E-01	0.27251E-01
PrincStress_1	0.11993	0.12815
PrincStress_2	0.53274E-02	0.86300E-02
PrincStress_3	-0.40122E-02	-0.44629E-02
PrincStrain_1	0.47789E-04	0.50679E-04
PrincStrain_2	-0.14098E-04	-0.13865E-04

Figure-A III- 6 28 Tensile strains at the bottom of the asphalt concrete after one 13-ton axle load

WinJulea indicates a maximum for the tensile strain of 20.935 microns (read max of Strain_X and Strain_Y. The number of allowable repetitions is calculated with the Asphalt Institute Equation *shown below*

$$N_f = 0.0796 * (0.20935 * 10^{-4})^{-3,291} * (2500 * 10^6 * 0.000145038)^{-0.854}$$

$$N_f = 3.6 * 10^9$$

The cumulated traffic over 20 years is equal to:

$$Cumulated\ traffic_{20\ years} = 4.5 * 10^{7}\ ESAL$$

$$\frac{N_f}{Cumulated\ traffic_{20\ years}} = \frac{3.6 * 10^{9}}{4.5 * 10^{7}} = 79$$

The calculations show a minimum of 3.6 billion repetitions of a 13-ton axle load. Therefore, there is no possibility of a rupture by fatigue before 20 years.

ANNEX IX

Assessment of the structural capacity of flexible pavement alternative D, with WinJulea

In order to confirm the structural capacity of the flexible pavement alternative B, a throughout mechanistic analysis is presented below.

Pavement characteristics

The top layer of the structure is a 125-mm conventional asphalt concrete, deploying a modulus of elasticity of 2,500 MPa. The asphalt concrete layer covers a 300-mm cement reclaimed base course, with a modulus of elasticity of 2,500 MPa. The subbase has a weak capacity with an assumed modulus of elasticity of 50 MPa.

Load characteristics

The total weight per ESAL, corresponding to the reference axle, is 13 tons. Therefore, the total weight per tire is equal to 3.25 tons.

The higher **contact pressure** is **830 kPa**. *(refer to sections 2.6.1.2-2.6.1.6).*

Contact area = 384.10 cm^2

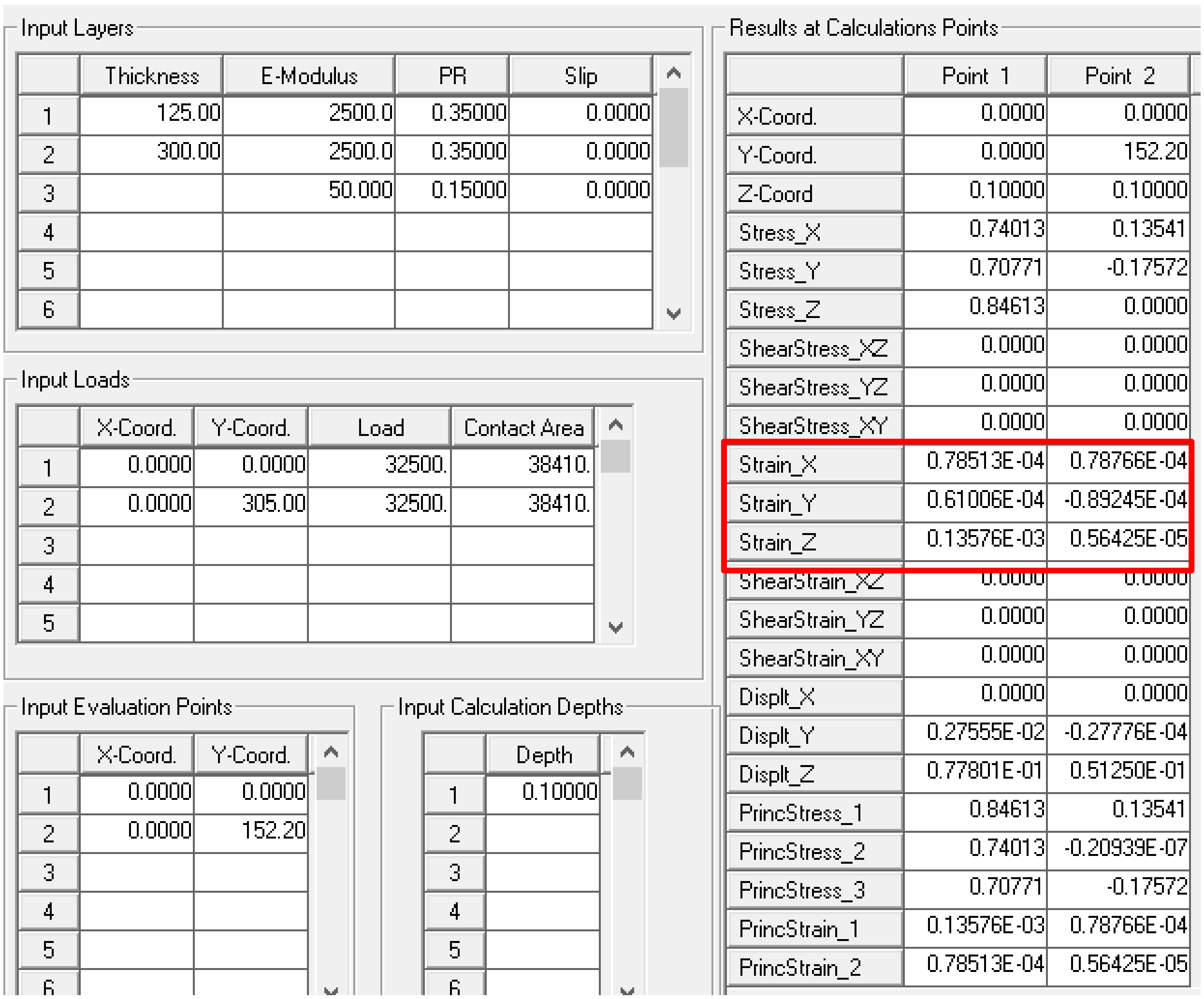
Modes of failure

The structural design of the pavement needs to verify the following modes of failure:

16. Failure in compression at the top of the asphalt concrete;
17. Failure in tension at the bottom of the asphalt concrete;
18. Failure in compression at the top of the base course;
19. Failure in tension at the bottom of the base course; and,
20. Failure in compression at the top of the subbase.

As shown in the following mechanistic analysis, there is no possibility of a rupture by fatigue before 20 years.

Failure in compression at the top of the asphalt concrete



Input Layers

	Thickness	E-Modulus	PR	Slip
1	125.00	2500.0	0.35000	0.0000
2	300.00	2500.0	0.35000	0.0000
3		50.000	0.15000	0.0000
4				
5				
6				

Input Loads

	X-Coord.	Y-Coord.	Load	Contact Area
1	0.0000	0.0000	32500.	38410.
2	0.0000	305.00	32500.	38410.
3				
4				
5				

Input Evaluation Points

	X-Coord.	Y-Coord.
1	0.0000	0.0000
2	0.0000	152.20
3		
4		
5		
6		

Input Calculation Depths

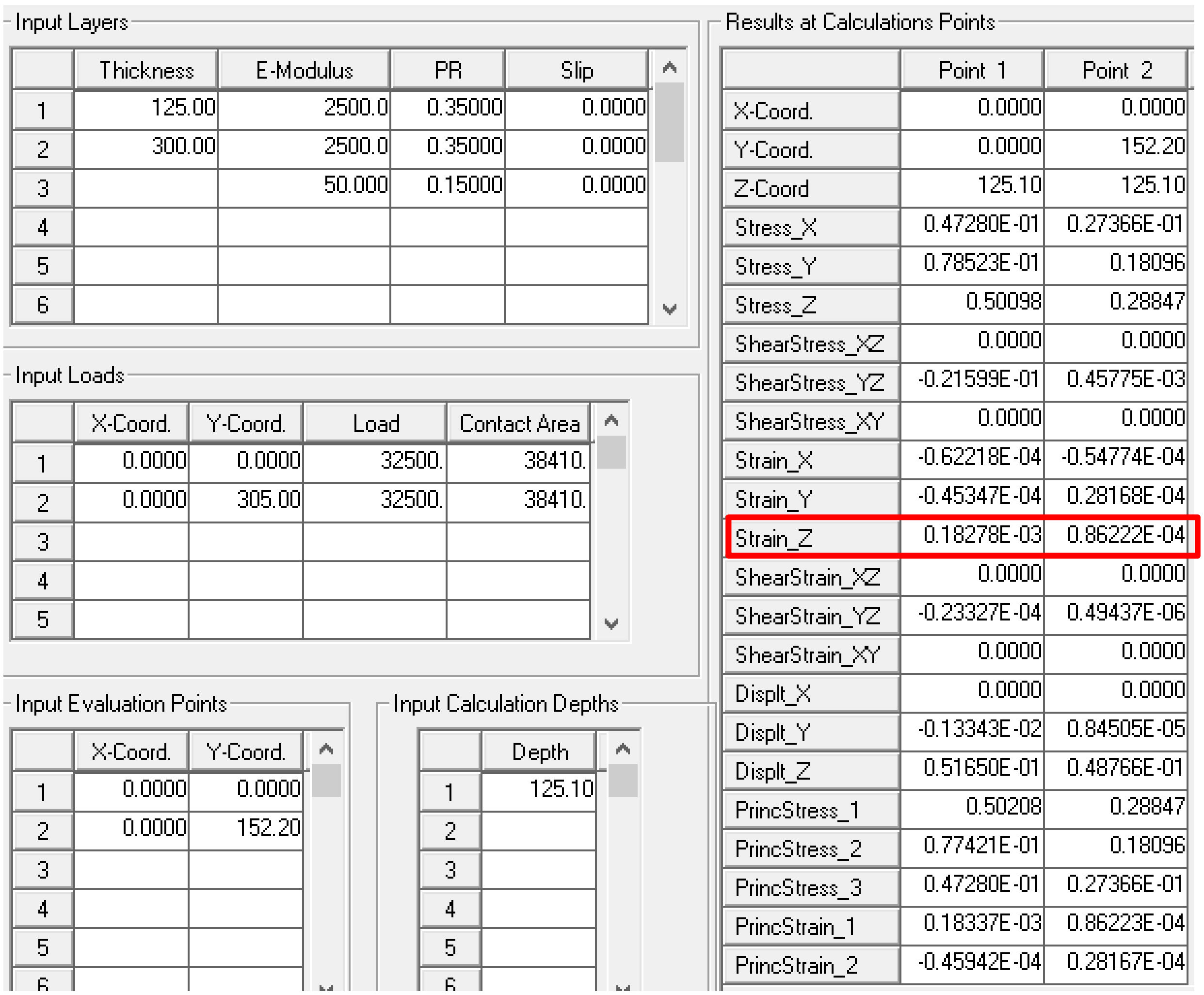
	Depth
1	0.10000
2	
3	
4	
5	
6	

Results at Calculations Points

	Point 1	Point 2
X-Coord.	0.0000	0.0000
Y-Coord.	0.0000	152.20
Z-Coord	0.10000	0.10000
Stress_X	0.74013	0.13541
Stress_Y	0.70771	-0.17572
Stress_Z	0.84613	0.0000
ShearStress_XZ	0.0000	0.0000
ShearStress_YZ	0.0000	0.0000
ShearStress_XY	0.0000	0.0000
Strain_X	0.78513E-04	0.78766E-04
Strain_Y	0.61006E-04	-0.89245E-04
Strain_Z	0.13576E-03	0.56425E-05
ShearStrain_XZ	0.0000	0.0000
ShearStrain_YZ	0.0000	0.0000
ShearStrain_XY	0.0000	0.0000
Displt_X	0.0000	0.0000
Displt_Y	0.27555E-02	-0.27776E-04
Displt_Z	0.77801E-01	0.51250E-01
PrincStress_1	0.84613	0.13541
PrincStress_2	0.74013	-0.20939E-07
PrincStress_3	0.70771	-0.17572
PrincStrain_1	0.13576E-03	0.78766E-04
PrincStrain_2	0.78513E-04	0.56425E-05

Figure-A III- 6 29 Compressive strains at the top of the asphalt concrete after one 13-ton axle load

Failure in compression at the top of the base course



Input Layers

	Thickness	E-Modulus	PR	Slip
1	125.00	2500.0	0.35000	0.0000
2	300.00	2500.0	0.35000	0.0000
3		50.000	0.15000	0.0000
4				
5				
6				

Input Loads

	X-Coord.	Y-Coord.	Load	Contact Area
1	0.0000	0.0000	32500.	38410.
2	0.0000	305.00	32500.	38410.
3				
4				
5				

Input Evaluation Points

	X-Coord.	Y-Coord.
1	0.0000	0.0000
2	0.0000	152.20
3		
4		
5		
6		

Input Calculation Depths

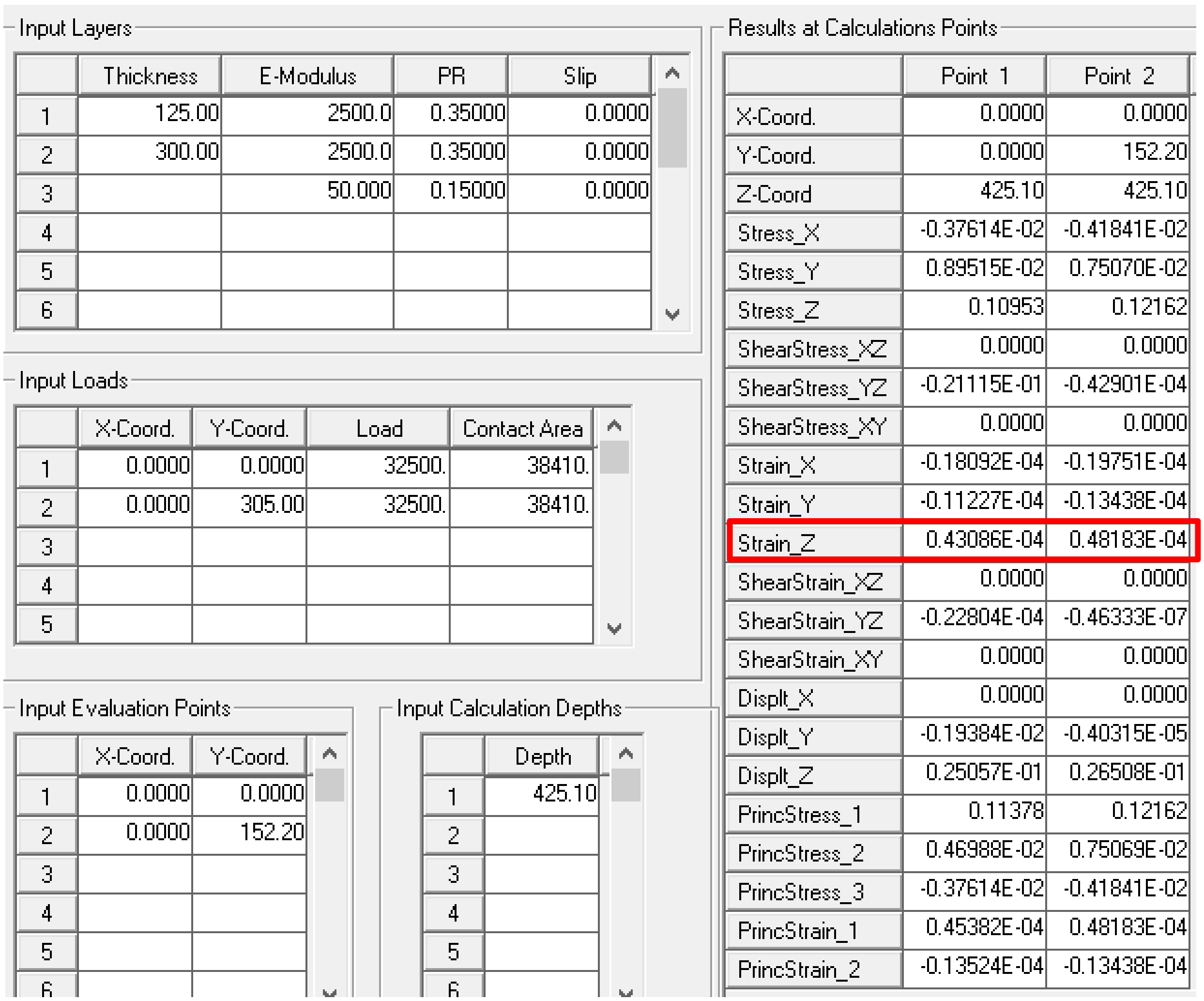
	Depth
1	125.10
2	
3	
4	
5	
6	

Results at Calculations Points

	Point 1	Point 2
X-Coord.	0.0000	0.0000
Y-Coord.	0.0000	152.20
Z-Coord	125.10	125.10
Stress_X	0.47280E-01	0.27366E-01
Stress_Y	0.78523E-01	0.18096
Stress_Z	0.50098	0.28847
ShearStress_XZ	0.0000	0.0000
ShearStress_YZ	-0.21599E-01	0.45775E-03
ShearStress_XY	0.0000	0.0000
Strain_X	-0.62218E-04	-0.54774E-04
Strain_Y	-0.45347E-04	0.28168E-04
Strain_Z	0.18278E-03	0.86222E-04
ShearStrain_XZ	0.0000	0.0000
ShearStrain_YZ	-0.23327E-04	0.49437E-06
ShearStrain_XY	0.0000	0.0000
Displt_X	0.0000	0.0000
Displt_Y	-0.13343E-02	0.84505E-05
Displt_Z	0.51650E-01	0.48766E-01
PrincStress_1	0.50208	0.28847
PrincStress_2	0.77421E-01	0.18096
PrincStress_3	0.47280E-01	0.27366E-01
PrincStrain_1	0.18337E-03	0.86223E-04
PrincStrain_2	-0.45942E-04	0.28167E-04

Figure-A III- 6 30 Compressive strains at the top of the base course after one 13-ton axle load

Failure in compression at the top of the subbase



Input Layers

	Thickness	E-Modulus	PR	Slip
1	125.00	2500.0	0.35000	0.0000
2	300.00	2500.0	0.35000	0.0000
3		50.000	0.15000	0.0000
4				
5				
6				

Input Loads

	X-Coord.	Y-Coord.	Load	Contact Area
1	0.0000	0.0000	32500.	38410.
2	0.0000	305.00	32500.	38410.
3				
4				
5				

Input Evaluation Points

	X-Coord.	Y-Coord.
1	0.0000	0.0000
2	0.0000	152.20
3		
4		
5		
6		

Input Calculation Depths

	Depth
1	425.10
2	
3	
4	
5	
6	

Results at Calculations Points

	Point 1	Point 2
X-Coord.	0.0000	0.0000
Y-Coord.	0.0000	152.20
Z-Coord	425.10	425.10
Stress_X	-0.37614E-02	-0.41841E-02
Stress_Y	0.89515E-02	0.75070E-02
Stress_Z	0.10953	0.12162
ShearStress_XZ	0.0000	0.0000
ShearStress_YZ	-0.21115E-01	-0.42901E-04
ShearStress_XY	0.0000	0.0000
Strain_X	-0.18092E-04	-0.19751E-04
Strain_Y	-0.11227E-04	-0.13438E-04
Strain_Z	0.43086E-04	0.48183E-04
ShearStrain_XZ	0.0000	0.0000
ShearStrain_YZ	-0.22804E-04	-0.46333E-07
ShearStrain_XY	0.0000	0.0000
Displt_X	0.0000	0.0000
Displt_Y	-0.19384E-02	-0.40315E-05
Displt_Z	0.25057E-01	0.26508E-01
PrincStress_1	0.11378	0.12162
PrincStress_2	0.46988E-02	0.75069E-02
PrincStress_3	-0.37614E-02	-0.41841E-02
PrincStrain_1	0.45382E-04	0.48183E-04
PrincStrain_2	-0.13524E-04	-0.13438E-04

Figure-A III- 6 31 Compressive strains at the top of the subbase after one 13-ton axle load

Allowable number of repetitions to prevent compression failure of the subgrade is calculated with the equation provided below:

$$N_f = 1.365\,x10^{-9}(\varepsilon_c)^{-4.477} \quad (11.0)$$

Where;

N_f = Number of load applications to failure

ε_c = Vertical Compressive strain at the bottom of asphalt bound layer

Figure-A III- 6 32 Asphalt Institute Equation to determine structural fatigue life based on compressive strain (Ekwulo and Eme 2009)

We assume that the Asphalt Institute Equation to determine structural fatigue life based on compressive strain is the same for the asphalt concrete layer, the base and the subbase. This equation does not depend on the properties on the layer *(as the modulus of elasticity, for the Asphalt Institute Equation to determine structural fatigue life based on tensile strain).*

Therefore, the mode of failure resulting from the rupture in compression of the pavement shows a maximum compressive strain of 182.78 microns (*read highest Strain_Z*), See figure A- III-6 33

$N_f = 1.365 * 10^{-9} * (0.18278 * 10^{-3})^{-4,477}$

$N_f = 7.4 * 10^{7}$

The cumulated traffic over 20 years is equal to:

$Cumulated\ traffic_{20\ years} = 4.5 * 10^{7}\ ESAL$

$$\frac{N_f}{Cumulated\ traffic_{20\ years}} = \frac{7.4 * 10^{7}}{4.5 * 10^{7}} = 1.6$$

The calculations show a maximum of 74 million repetitions of a 13-ton axle load. Therefore, there is no possibility of a rupture by fatigue before 20 years.

Failure in tension at the bottom of the asphalt concrete

Input Layers

	Thickness	E-Modulus	PR	Slip
1	125.00	2500.0	0.35000	0.0000
2	300.00	2500.0	0.35000	0.0000
3		50.000	0.15000	0.0000
4				
5				
6				

Input Loads

	X-Coord.	Y-Coord.	Load	Contact Area
1	0.0000	0.0000	32500.	38410.
2	0.0000	305.00	32500.	38410.
3				
4				
5				

Input Evaluation Points

	X-Coord.	Y-Coord.
1	0.0000	0.0000
2	0.0000	152.20
3		
4		
5		
6		

Input Calculation Depths

	Depth
1	124.90
2	
3	
4	
5	
6	

Results at Calculations Points

	Point 1	Point 2
X-Coord.	0.0000	0.0000
Y-Coord.	0.0000	152.20
Z-Coord	124.90	124.90
Stress_X	0.47524E-01	0.27480E-01
Stress_Y	0.78729E-01	0.18130
Stress_Z	0.50169	0.28847
ShearStress_XZ	0.0000	0.0000
ShearStress_YZ	-0.21560E-01	0.45247E-03
ShearStress_XY	0.0000	0.0000
Strain_X	-0.62249E-04	-0.54776E-04
Strain_Y	-0.45398E-04	0.28288E-04
Strain_Z	0.18300E-03	0.86157E-04
ShearStrain_XZ	0.0000	0.0000
ShearStrain_YZ	-0.23285E-04	0.48867E-06
ShearStrain_XY	0.0000	0.0000
Displt_X	0.0000	0.0000
Displt_Y	-0.13304E-02	0.83888E-05
Displt_Z	0.51687E-01	0.48783E-01
PrincStress_1	0.50278	0.28847
PrincStress_2	0.77633E-01	0.18130
PrincStress_3	0.47524E-01	0.27480E-01
PrincStrain_1	0.18359E-03	0.86158E-04
PrincStrain_2	-0.45990E-04	0.28287E-04

Figure-A III- 6 33 Tensile strains at the bottom of the asphalt concrete after one 13-ton axle load

WinJulea indicates a maximum for the tensile strain of 62.249 microns *(read max of Strain_X and Strain_Y).*

The number of allowable repetitions is calculated with the Asphalt Institute Equation provided Figure-A III- 6 34.

The asphalt institute (Asphalt Institute, 1982) suggested that the relationship between fatigue failure of asphalt concrete and tensile strain is represented by the number of load repetitions as follows:

$$N_f = 0.0796(\varepsilon_t)^{-3.291}(E)^{-0.854} \qquad (8.0)$$

Where;
N_f = Number of load applications to failure
ε_t = Horizontal tensile strain at the bottom of asphalt bound layer
E = Elastic Modulus of asphalt concrete

Figure-A III- 6 35 Asphalt Institute Equation to determine structural fatigue life based on tensile strain (Ekwulo and Eme 2009)

$$N_f = 0{,}0796 * (0.62249 * 10^{-4})^{-3{,}291} * (2500 * 10^{6} * 0{,}000145038)^{-0.854}$$

$$N_f = 9.9 * 10^{7}$$

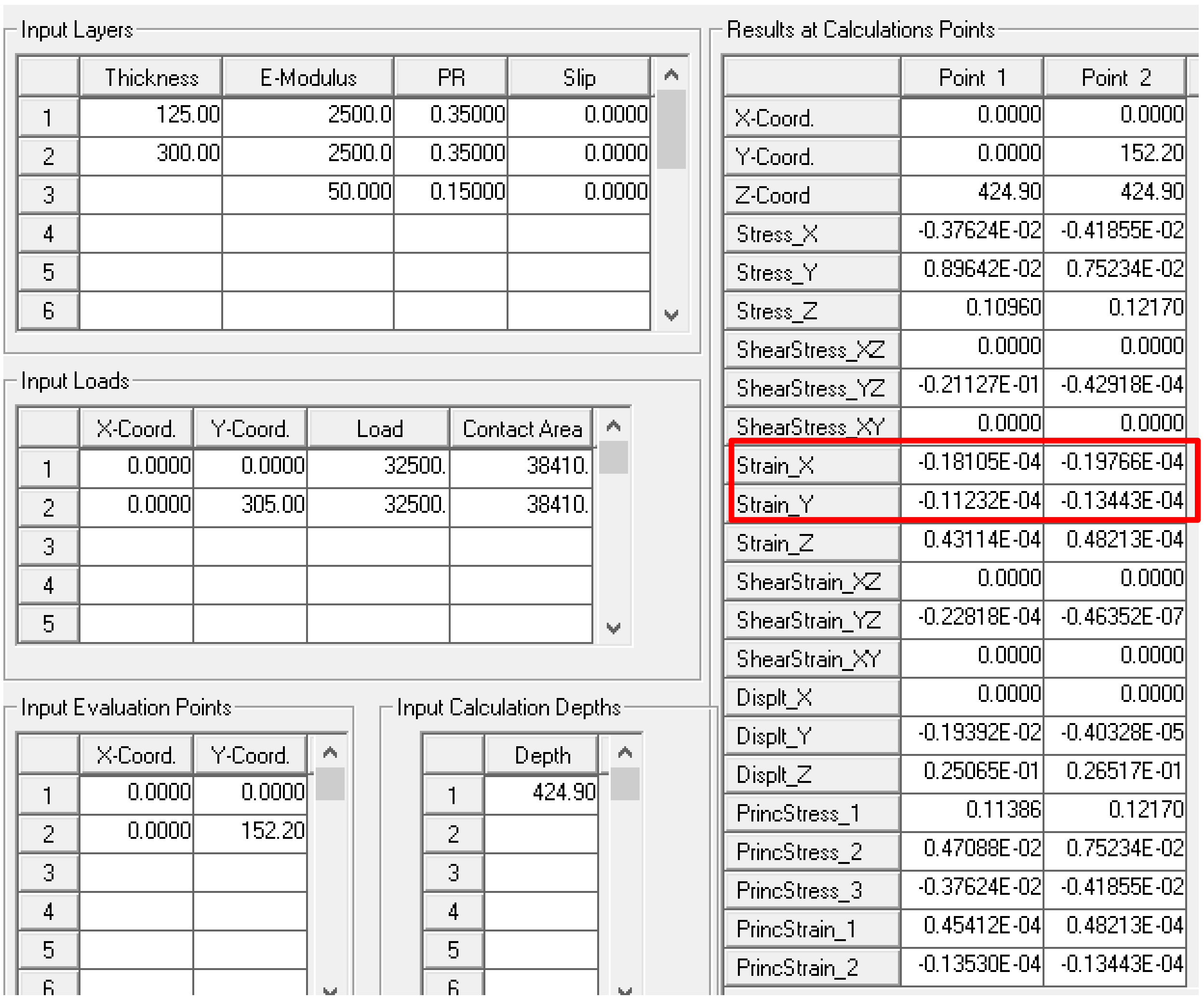
The cumulated traffic over 20 years is equal to:

$$Cumulated\ traffic_{20\ years} = 4.5 * 10^{7}\ ESAL$$

$$\frac{N_f}{Cumulated\ traffic_{20\ years}} = \frac{9.9 * 10^{7}}{4.5 * 10^{7}} = 2.2$$

The calculations show a minimum of 99 million repetitions of a 13-ton axle load. Therefore, there is no possibility of a rupture by fatigue before 20 years.

Failure in tension at the bottom of the base course



Input Layers

	Thickness	E-Modulus	PR	Slip
1	125.00	2500.0	0.35000	0.0000
2	300.00	2500.0	0.35000	0.0000
3		50.000	0.15000	0.0000
4				
5				
6				

Input Loads

	X-Coord.	Y-Coord.	Load	Contact Area
1	0.0000	0.0000	32500.	38410.
2	0.0000	305.00	32500.	38410.
3				
4				
5				

Input Evaluation Points

	X-Coord.	Y-Coord.
1	0.0000	0.0000
2	0.0000	152.20
3		
4		
5		
6		

Input Calculation Depths

	Depth
1	424.90
2	
3	
4	
5	
6	

Results at Calculations Points

	Point 1	Point 2
X-Coord.	0.0000	0.0000
Y-Coord.	0.0000	152.20
Z-Coord	424.90	424.90
Stress_X	-0.37624E-02	-0.41855E-02
Stress_Y	0.89642E-02	0.75234E-02
Stress_Z	0.10960	0.12170
ShearStress_XZ	0.0000	0.0000
ShearStress_YZ	-0.21127E-01	-0.42918E-04
ShearStress_XY	0.0000	0.0000
Strain_X	-0.18105E-04	-0.19766E-04
Strain_Y	-0.11232E-04	-0.13443E-04
Strain_Z	0.43114E-04	0.48213E-04
ShearStrain_XZ	0.0000	0.0000
ShearStrain_YZ	-0.22818E-04	-0.46352E-07
ShearStrain_XY	0.0000	0.0000
Displt_X	0.0000	0.0000
Displt_Y	-0.19392E-02	-0.40328E-05
Displt_Z	0.25065E-01	0.26517E-01
PrincStress_1	0.11386	0.12170
PrincStress_2	0.47088E-02	0.75234E-02
PrincStress_3	-0.37624E-02	-0.41855E-02
PrincStrain_1	0.45412E-04	0.48213E-04
PrincStrain_2	-0.13530E-04	-0.13443E-04

Figure-A III- 6 36 Tensile strains at the bottom of the asphalt concrete after one 13-ton axle load

WinJulea indicates a maximum for the tensile strain of 19.766 microns [read max of Strain_X and Strain_Y]. The number of allowable repetitions is calculated with the Asphalt Institute Equation *shown below*

$$N_f = 0.0796 * (0.19766 * 10^{-4})^{-3,291} * (2500 * 10^6 * 0.000145038)^{-0.854}$$

$$N_f = 4.3 * 10^9$$

The cumulated traffic over 20 years is equal to:

$$Cumulated\ traffic_{20\ years} = 4.5 * 10^7\ ESAL$$

$$\frac{N_f}{Cumulated\ traffic_{20\ years}} = \frac{4.3 * 10^9}{4.5 * 10^7} = 96$$

The calculations show a minimum of 430 million repetitions of a 13-ton axle load. Therefore, there is no possibility of a rupture by fatigue before 20 years.

ANNEX X

RS Means Data

RS Means Data (Robert Snow Means Data- meticulous construction costs) screenshots and calculations to accommodate RS Means estimates for Tunisia

Assumptions:

- Truck type: 12 C.Y = 9.2 m³
- Distance from the quarry to the Port: 40km or 80-km round trip (about 50 miles)
- Waiting, loading/dumping time per cycle: 30 min.
- Average speed: WSP has considered the minimal available speed in the RS means for an 80-km round trip *(40 mph or 65 km/h)* because of congestion in Tunis. In our opinion this is quite high and we would be underestimating the cost with 65 km/h.

Based on RSMeans *(page 1134)*, hauling cost, *including overhead and profit,* is about 25.50 USD/Loose Yard Cube or 33.35 USD/m³. Therefore, based on Means, total cost for the transport of material from a 40-km away quarry, is **0.83 USD/m³/km**.

Note: All Means tables are pasted below for reference.

In order to match lower prices obtained in Tunis by Fued and other source on the Internet:

WSP used a correction factor applied only on driver wage and overhead costs of 0.*065 (ratio between American- 56,810 USD/year - and Tunisian – 3,690 USD/year – average annual wages)*.

Therefore, the corrected cost of transport becomes: 13.79 USD/Loose Yard Cube or **0.45 USD/m³/km** *(correction factor *(total cost – equipment cost*(1+10%)) + equipment cost *(1+10%) = 0.065*(25.5-11.8*1.1) + 11.8*1.1= 13.79 USD/Loose Yard Cube). Convert in m3 by multiplying result by 1.3 m3/CY and divide by 40 km.*

Note: RSMeans calculation method requires a 10% factor for equipment.

If WSP considers applying a correction factor of 80% on equipment, the corrected cost of transport becomes: **0.363 USD/m³/km** *(correction factor *(total cost – equipment* *cost*(1+10%)) + equipment cost *(1+10%) = 0.065*(25.5-11.8*1.1) + 0.80*(11.8*1.1) = 11.20 USD/Loose Yard Cube). Convert in m3 by multiplying result by 1.3 m3/CY and divide by 40 km.*

If the average speed is reduced to 30 km/h, the corrected cost of transport becomes: **0.38 USD/m³/km**

Add 2023 to 2019 cost adjustment of 2% per year: 0.38 * 1.02^4 = **0.41 USD/m3.km**

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