Utilisation du BIM pour l’étude de conformité de maquettes numériques dans l’industrie de la construction en bois massif

par

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RÉSUMÉ

Depuis une dizaine d'années, les nouvelles constructions en bois se multiplient au Québec, notamment celles en bois massif. Les panneaux de CLT et colonnes de lamellé-collé qui constituent les structures en bois massif sont préfabriquées hors-site à l’usine. Cela rend l’approche de travail par modélisation des données du bâtiment, Building Information Modeling (BIM) particulièrement adapté. Utiliser le BIM permet de gagner en efficacité, notamment à l’étape de vérification du modèle qui consiste à étudier sa conformité aux différentes exigences. Dans le cas des constructions hors-site, il faut notamment tenir compte de la capacité manufacturière de l'usine de préfabrication. De façon générale, l’étape de vérification de modèle basée sur le BIM a été étudiée de manière assez spécifique seulement: étude de conformité d’un modèle selon un code, degré d’automatisation de la vérification. Aujourd'hui, il manque une méthode générale qui synthétise les possibilités offertes par la vérification de modèle basée sur le BIM de façon général. Il y a aussi un manque de travaux de recherche concernant l'étude de conformité des maquettes numériques en bois massif en particulier.

L'objectif de notre recherche est de fournir une méthode générale, supportée par des outils, résumant étape par étape le processus d'étude de conformité des modèles numériques. Pour mener à bien ce travail de recherche, nous avons d’abord réalisé des entrevues avec des professionnels de l'industrie de la construction en bois massif. Ensuite, nous avons développé par itération la méthode supportée par des outils et nous l'avons validée avec trois études de cas de vérification de modèles. La méthode comprend cinq étapes: premièrement, spécifier le besoin de vérification ; deuxièmement, s'assurer d'avoir un environnement numérique BIM adéquat; troisièmement, déchiffrer le contenu de l'exigence à vérifier ; quatrièmement, effectuer le calcul pour étudier la conformité ou la non-conformité du modèle ; et la dernière étape, analyser les résultats de la conformité ou non. Les études de cas réalisées ont consisté à étudier trois scénarios différents de vérification de modèles en appliquant pas à pas la méthode proposée.

Dans ce travail de recherche, nous avons abordé plusieurs aspects de la vérification de modèles. Nous constatons notamment que les logiciels dédiés au model-checking sont nombreux et prometteurs. Ils permettent beaucoup et ont un grand potentiel pour rentabiliser l'étape de vérification grâce à l'approche BIM. Cependant, les obstacles rencontrés montrent que le BIM, pour être efficace, doit être réalisé sur des modèles avec une haute qualité de l’information, ce qui n'est pas assez souvent le cas.

Mots-clé : Modélisation des données du bâtiment, BIM, Bois massif, Étude de conformité au code, Maquette numérique, Méthodologie

Use of BIM to study the conformity of digital models in the mass timber construction industry

Chloé PASKOFF

ABSTRACT

For the last ten years, new wood constructions are multiplying in Quebec, especially mass timber ones. The CLT panels and glulam columns that make up the mass timber structures are prefabricated off-site at the factory. This particularity makes the Building Information Modeling (BIM) approach particularly suitable to conduct mass timber constructions projects. Using BIM makes for greater efficiency, particularly at the model verification stage, which involves studying its compliance with various requirements. In the case of off-site construction, the manufacturing capacity of the prefabrication plant must be taken into account. Generally speaking, the BIM-based model verification stage has only been studied in fairly specific terms: code compliance study, degree of verification automation. Today, there is a lack of a general method that synthesizes the possibilities offered by BIM-based model checking in general and we deplore also a lack of research concerning the conformity study of mass timber models in particular.

Our research objective is to provide a general step-by-step method summarizing the process of model compliance study with dedicated tools. To conduct this research work, we first made sure we understood the problem by consulting the literature and by interviewing professionals from the mass timber construction industry. Then, we developed by iteration the method supported by tools and validated it with three model-checking case studies. The method consists of five steps: first, specify the checking need; two, ensure to have a consistent digital environment; three, decipher the content of the requirement; four, carry out the calculation to study the conformity or the non-conformity of the model; and the last step, analyze of the compliance results. The case studies conducted consisted of studying three different scenarios of model checking through the application of the suggested method.

Through this research paper, we have addressed several aspects of model checking. We note in particular that the software dedicated to model-checking are numerous and promising. They allow a lot and have a great potential to make the model checking step profitable due to the BIM approach. However, the obstacles encountered show that BIM, in order to be efficient, must be conducted on high-quality models which is not often enough the case.

Keywords: Building information modeling, BIM, Mass timber, Code compliance checking, Digital mock-up, Methodology

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BIM	Building Information Modeling
CLT	Cross-Laminated Timber
BMC	BIM-based model checking

INTRODUCTION

Avec le développement actuel des outils digitaux pour la construction, il devient de plus en plus inévitable de travailler avec une maquette numérique pour concevoir, construire et opérer un bâtiment. La modélisation des données du bâtiment, Building Information Modeling (BIM) en anglais, est l'approche digitale au projet de construction : elle permet justement de centraliser les données, de planifier les travaux, de coordonner les métiers, et ce tout au long du projet autour d'un même modèle numérique.

La vérification de modèles numériques est donc une étape importante au processus de conception et de validation de la maquette numérique de travail. Il faut étudier sa conformité, aux codes de construction notamment, mais aussi à des exigences diverses. Si aujourd'hui effectuer une vérification à la main prend du temps, les outils BIM permettraient d'automatiser le processus et de l'étendre à un grand nombre de maquettes. Un modèle numérique pouvant être vérifié et contrôlé de plusieurs façons, il serait intéressant de réaliser une étude des différentes capacités et possibilités de vérification (vérification géométrique, vérification de règles, vérification de conformité pour standard de certification, etc.). Pour les acteurs de l'industrie de l'AEC, Architecture, Engineering and Construction en anglais, en phase de conception, il serait intéressant de pouvoir savoir quel type de vérification est possible avec quel outil et quelle vérification est automatisable ou non. Certaines catégories de projets requièrent d'autant plus l'utilisation du BIM et donc nécessitent de pouvoir conduire correctement des études de conformités de modèles. C'est le cas des constructions de bois massif dont la technologie nouvelle (construction hors-site, matériaux nouveaux non-standardisés, etc.) implique des vérifications particulières. Aucun travail de recherche ne s'est intéressé à la vérification de modèle en bois massif. Quelques-uns ont étudié l'automatisation du processus pour des modèles quelconques.

L'objectif principal est d'étudier le potentiel des méthodes d'étude de conformité pour l'industrie du bois massif. Les objectifs spécifiques sont d'abord de proposer une méthode générale d'évaluation de conformité d'un modèle numérique, puis d'en faire la preuve de concept en appliquant cette méthode à des projets de bois massif.

Le présent mémoire sera structuré de la façon suivante : le chapitre premier sera dédié à la revue de littérature, laquelle définira les particularités du bois massif comme matériau, puis les enjeux relatifs à la vérification de modèle basée sur le BIM. Le deuxième chapitre présentera la méthodologie de recherche suivie pour ce mémoire. Les objectifs principaux et spécifiques y seront détaillés. Dans le troisième chapitre figurera l'article scientifique de journal issu de cette recherche. La méthode générale d'étude de conformité de modèle ainsi que la preuve du concept y seront décrites. Enfin, le chapitre quatre sera consacré à une discussion des résultats de recherche : les limites et travaux futurs en lien seront abordés.

CHAPITRE 1

REVUE DE LITTÉRATURE

1.1 Le bois massif

L'industrie du bois est considérable au Canada. En 2020, l'industrie des produits du bois contribuait à hauteur de 6 % aux revenus des biens manufacturés pour une valeur de 635,1 milliards de dollars (S. C. Government of Canada, 2022). Au Québec en particulier, les forêts couvrent plus de la moitié du territoire soit plus de 900 000 km² (Ressources naturelles et Forêts, 2023). Pourtant, ce n'est qu'en 2012 que la technologie du bois massif apparaît au Canada, alors qu'elle s'est développée dans les années 90 en Europe. En 2019, la production de panneaux CLT était de 1,44 million de m3 dans le monde et selon les Nations Unies, ce volume doublera d'ici 2025 (United Nations, 2021). Le bois massif est une technologie prometteuse, autant d'un point de vue structurel que d'un point de vue de la durabilité. L'objectif de cette sous-section est de présenter ce matériau, ses caractéristiques et les exigences de vérification qui en découlent.

Dans la littérature ont été identifié deux types de structures en bois : la structure à ossature légère et la structure de bois massif. Contrairement aux structures à ossature légère, qui sont composées d'éléments en bois relativement petits (poutres, lattes, solives de plancher, rondins, fermes de toit et poutres ajourées), les structures en bois massif se caractérisent par l'utilisation de grands panneaux et de colonnes de bois assemblés. Elles sont constituées de produits en bois d'ingénierie tels que les panneaux de *cross-laminated timber* CLT, bois lamellé-croisé, ou les poutres de *glued-laminated timber*, bois lamellé-collé. Le bois massif est plus lourd et plus solide : il est plus facile de construire en hauteur en comparaison avec une ossature en bois légère.

Le terme "produit de bois d'ingénierie" *engineering wood product* (EWP) désigne tous les produits en bois qui ont été modifié et manufacturés pour répondre aux besoins de l'industrie. Il s'agit de produits multicouches préfabriqués. Les deux technologies nouvelles de bois massif sont le CLT et le lamellé-collé (Churkina et al., 2020). FP Innovations le définit dans le Canadian CLT Handbook (Karacabeyli & Gagnon, 2019): le CLT consiste en une superposition de couches perpendiculaires de lamelles de bois juxtaposées. Elles sont assemblées avec de la colle, des vis ou même des clous sur un nombre impair de couches, dont trois minimum. Le CLT se distingue du bois lamellé-collé par la perpendicularité de ses couches. Le bois lamellé-collé est unidirectionnel et possède un axe principal.

Les constructions en bois massif bénéficient des performances de cette technologie de fabrication (rigidité, légèreté), en plus des performances dues à l'utilisation du bois comme matériau (durabilité, isolation et esthétique).

Tout d'abord, le bois est un matériau à faible empreinte carbone. Si le bois a été le premier matériau de construction, le choisir aujourd'hui pour construire des édifices permet de réduire les émissions de gaz à effet de serre (GES) liées à la construction. L'Agence internationale de l'énergie indique que chaque année, l'industrie mondiale de la construction émet à elle seule 39 % des GES (IAE, 2018). Les deux tiers proviennent des opérations de construction et le tiers restant vient des matériaux utilisés (béton, acier et aluminium). Au contraire, le bois, ressource naturelle abondante, est renouvelable et capte le carbone (Churkina et al., 2020). Il nécessite peu de transformation de son état brut à l'état de matériau de construction. Opter pour ce matériau permet donc de se rapprocher de l'objectif de neutralité carbone à l'horizon 2050.

Le développement récent du bois massif a permis d'augmenter le nombre d'étages dans les bâtiments car la bidirectionnalité des panneaux CLT offre une stabilité et une rigidité similaires à celles du béton armé. Contrairement au bois d'œuvre, le bois d'ingénierie est uniforme et plus résistant. Selon l'APA - The Engineered Wood Association, le bois lamellé-collé est plus résistant que l'acier à masse égale (« Glulam - APA – The Engineered Wood Association », s.d.). Les panneaux CLT sont utilisés comme sections de murs, dalles de plancher et plafonds. Le bois lamellé-collé est utilisé principalement pour les poutres, les poteaux et les arcs.

Le CLT est 80 % plus léger que le béton, à masse égale (ρ_CLT=480 kg/m3 vs ρ_concrete=2700 kg/m3) (Binderholz, s.d.). Avec cette légèreté, les fondations sont moins encombrantes et moins volumineuses : ainsi, moins de quantité de béton est nécessaire. Le bois est également un excellent isolant, tant acoustique que thermique. Son coefficient d'isolation thermique est bon : λ_CLT=0,120 W/m.K (Götz, Hoor, Möhler, & Nattere, 1987). En comparaison, le béton est moins isolant : λ_concrete=1.500 W/m.K. Le bois absorbe les vibrations : les panneaux de bois sont des surfaces qui réfléchissent le son (Canadian Wood Council, 1994). Un autre avantage du CLT est sa flexibilité, qui le rend résistant aux vibrations. Cet aspect est particulièrement important dans la région de la Colombie-Britannique où les questions sismiques sont importantes (N. R. C. Government of Canada, 2015). Au Canada, le bois lamellé-collé est fabriqué à partir de douglas-sapin-mélèze (Canadian Wood Council, 1994) et le bois lamellé-croisé est principalement fabriqué à partir d'épicéa-pin-sapin (APA - The Engineered Wood Association, 2021). Le bois est un matériau chaleureux et accueillant. L'esthétique des poutres apparentes joue un rôle apaisant et favorise le bien-être des utilisateurs du bâtiment. Exposés, les panneaux CLT jouent à la fois le rôle de structure et de finition architecturale.

Ces matériaux ont quelques particularités. Alors que les structures à ossature légère sont entièrement construites sur place, les constructions en bois massif sont préfabriquées hors site puis assemblées. Les éléments sont manufacturés en usine où l'environnement contrôlé assure une fabrication de précision. L'idée générale est de transférer les ressources et le travail du chantier à l'usine. Dans cette section, les particularités de la construction hors site puis celles du bois massif seront décrites, afin de mieux comprendre les principaux enjeux de ce type de projet en termes de conception.

La construction hors site désigne un mode de construction dans lequel le bâtiment est construit pièce par pièce à l’usine, lesquelles sont ensuite assemblées sur chantier. La digitalisation et les outils numériques offrent une nouvelle approche des projets modulaires et hors site (McKinsey&Compagny, 2019). Concevoir un bâtiment hors site nécessite de tenir compte de l’étape de préfabrication en usine. Cette étape de production a des conséquences sur la conception du bâti : la préfabrication en usine, le transport des éléments préfabriqués et les réglementations non adaptées. La Figure 1.1 synthétise les particularités des constructions hors-site.

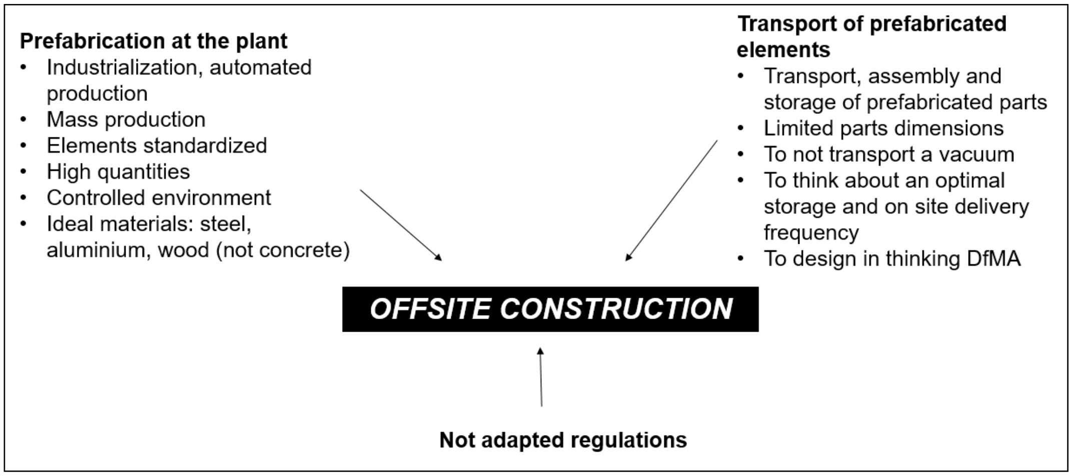

Figure 1.1 Les particularités des constructions hors-site

- **Préfabrication à l'usine.** La production de masse à l'usine est rentable (Smith & Quale, 2017). L'environnement contrôlé (température, humidité, électricité, etc.) permet d'automatiser le processus de fabrication : cela signifie un processus de fabrication plus rapide (McKinsey&Compagny, 2019). Il s'agit d'une industrialisation du processus de fabrication : des éléments standardisés en grande quantité. La préfabrication n'est pertinente qu'avec les matériaux suivants : l'acier, l'aluminium et le bois. Dans ce contexte, le béton n'est pas un matériau adapté.
- **Des réglementations inadaptées.** Les codes et réglementations actuels ne distinguent pas la construction hors site de la construction classique in situ (Wilson, 2020).

- **Transport des éléments préfabriqués.** Les éléments de construction fabriqués à l'usine doivent être transportés jusqu'au site. Il faut tenir compte non seulement du transport, mais aussi de l'assemblage et du stockage. Ces étapes limitent le volume et le poids. Les pièces modulaires doivent être conçues avec le compromis de ne pas transporter trop de vide. Pour optimiser la durée de stockage des éléments, il faut déterminer une fréquence optimale de livraison sur site. Ainsi, l'ensemble du processus de transport des éléments modulaires doit être pris en considération lors de la phase de conception. Cela renvoie à la notion de DfMA (Design for Manufacturing and Assembly): les modules préfabriqués sont conçus pour faciliter la fabrication, l'assemblage et la livraison. Les déplacements sur site sont anticipés ainsi que la manière de les assembler.

La construction en bois massif nécessite la préfabrication en usine d'éléments en bois massif (panneaux CLT et poteaux en bois lamellé-collé). Le bois comme matériau de construction a aussi des caractéristiques particulières. Tout cela a des conséquences sur l'étude de conformité du modèle. Nous les classons en trois catégories : la préfabrication hors site, le bois massif comme matériau et les réglementations correspondantes. La Figure 1.2 synthétise les particularités des constructions en bois massif.

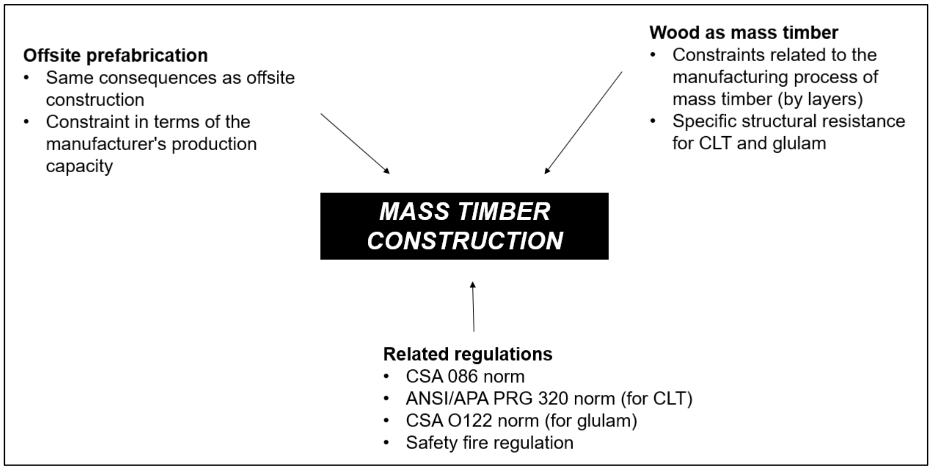

Figure 1.2 Les particularités des constructions bois massif

- **Préfabrication hors site.** Les éléments de bois massif sont construits hors site à l’usine. La conception doit également tenir compte des capacités manufacturières de l'usine CLT : les installations, l'infrastructure de production, la capacité de stockage, le volume de production, etc. L'équipement et l'infrastructure de l'usine limitent les dimensions des pièces. Alors qu'un bâtiment est généralement un prototype orienté client, les éléments préfabriqués à l'usine sont orientés produit.
- **Le bois massif comme matériau.** En outre, certaines exigences liées à l'utilisation du bois comme matériau doivent également être prises en compte. Le processus de fabrication des panneaux CLT par couches implique une résistance structurelle spécifique. Un ratio idéal entre la portée et l'épaisseur des panneaux est recommandé aussi par les fabricants.
- **Réglementation.** Il existe des réglementations et des codes spécifiques pour la construction en bois. Quelques-unes sont focalisées sur le bois massif. Elles sont détaillées ci-dessous. Alors que les pays européens et nord-américains ont ajusté leurs codes de constructions pour autoriser la construction d'immeubles de moyenne et parfois de grande hauteur en bois de nombreux autres pays doivent encore adopter une réglementation appropriée (Churkina et al., 2020).

Comme tous les bâtiments, les bâtiments en bois massif doivent être construits dans le respect des réglementations en vigueur. La revue de la littérature a montré qu'en plus des codes de construction courants, certaines réglementations spécifiques concernent les constructions en bois et en bois massif. La norme CSA086 du Code national du bâtiment du Canada précise les règles de calcul pour les structures en bois (Commission canadienne des codes du bâtiment et de prévention des incendies, 2022). La norme ANSI/APA PRG 320 est consacrée au CLT (American National Standards Institute, 2018) et la norme CSA O122 au bois lamellé-collé (CSA Group, 2016). Pelletier et al. se concentrent dans leur article sur les bâtiments en bois massif encapsulés jusqu'à 12 étages (Pelletier, Lessard, Gagnon, & Dagenais, 2022). L'expert Karacabeyli a proposé un manuel sur le CLT avec FP Innovations (Karacabeyli & Gagnon, 2019) et un guide pour les grands bâtiments en bois au Canada (Karacabeyli & Lum, 2022).

Cependant, les codes actuels ne font pas de distinction entre les systèmes de construction combustibles : c'est-à-dire la construction à ossature légère, les systèmes de poteaux et de poutres, le bois d'ingénierie structurelle, le bois lamellé-collé, le bois lamellé-croisé ou la construction hybride (Pelletier et al., 2022). Ces codes suggèrent plusieurs exigences relatives au bois massif qui ont un impact sur la conception. La norme ANSI/APA PRG 320 (American National Standards Institute, 2018) définit les exigences géométriques pour les panneaux CLT. L'épaisseur maximale est de 20 pouces (508mm), les tolérances dimensionnelles de longueur, de largeur et d'épaisseur d'un panneau CLT sont également spécifiées. L'épaisseur idéale des lamelles est comprise entre 5/8 pouces (16 mm) et 2 pouces (51 mm). Le guide de Karacabeyli propose un code basé sur les objectifs (par opposition à un code basé sur les performances) (Karacabeyli & Lum, 2022). Il préconise une utilisation maximale de la préfabrication pour réduire les coûts et augmenter l'efficacité de la construction. Pour optimiser les charges verticales, il recommande d'avoir autant de grandes portées que possible aux étages supérieurs. L'épaisseur disponible du panneau détermine la portée possible et sa performance.

Ces spécificités ont des conséquences sur la conception du bâtiment, et donc sur la maquette numérique. Plusieurs points doivent être pris en compte pour la modélisation. Tout d'abord, le transport, la logistique, la livraison, le stockage et le montage sont des enjeux importants à considérer. L'étape du transport limite la taille (et le poids) des modules préfabriqués. Il faut également tenir compte de la réglementation du transport routier, des convois exceptionnels, des autorisations, etc. La taille est limitée à 3,5m de largeur sur la route (Smith & Quale, 2017). Pour une construction modulaire 3D classique, il est important de ne pas transporter ou stocker trop de vide, mais avec des panneaux 2D préfabriqués de CLT, ce n'est pas une considération majeure. Ensuite, la répétabilité de la conception jour un rôle important, car la construction hors site en usine n'est pertinente que pour les bâtiments standardisés (bâtiments résidentiels, dortoirs, hôtels, hôpitaux, etc.) Ainsi, plus le bâtiment est répétitif, plus le choix du bois massif est intéressant et rentable.

Ainsi, lors de sa conception, le bâtiment doit être pensé dans une perspective de préfabrication. Contrairement aux constructions conventionnelles, il est nécessaire de travailler en collaboration avec chaque corps de métier, car les décisions de modélisation doivent être prises relativement tôt. Les projets hors site impliquent un haut niveau d'intégration : la collaboration entre les concepteurs et les fabricants, la définition des rôles et des responsabilités et l'utilisation d'une plateforme collaborative pour le modèle (Wilson, 2020). Pour ce faire, une plateforme collaborative telle qu'un outil BIM est nécessaire. De plus, l'approche conception-soumission-construction n'est pas adaptée à la préfabrication : l'approche IPD (Integrated Project Delivery) convient mieux. La BIM et la construction hors site sont étroitement liées (Alfieri, Seghezzi, Sauchelli, Di Giuda, & Masera, 2020).

Aujourd’hui, l'approche numérique bénéficie à chaque étape de la construction en bois massif. Les logiciels de conception assistée par ordinateur (CAO) et la conception paramétrique avec les outils de programmation visuelle sont utilisés au stade de la modélisation. Pour la préfabrication à l'usine, les dessins industriels en 2D des pièces préfabriquées peuvent être extraits du modèle numérique en 3D pour les machines à commande numérique. La gestion de la planification numérique est très utile pour livrer des modules juste à temps, afin de limiter les déplacements et d'optimiser le stockage. En particulier, le Building Information Modeling (BIM) offre la possibilité de fédérer des modèles numériques (architecturaux, structurels et MEP), de procéder à des simulations temporelles (BIM 4D) et de faire des analyses comparatives (coûts, émissions de gaz à effet de serre). Le BIM offre l'avantage de la centralisation autour d'un même modèle : cela permet de faire des vérifications du modèle et d'étudier sa conformité aux codes de construction et réglementations en vigueur, ainsi que selon la capacité de fabrication des usines hors site.

La deuxième partie de la revue de la littérature présente l'état de l'art en matière de vérification de modèles numériques et en termes de numérisation de la tâche.

1.2 La vérification de modèle basée sur le BIM

Au cours des dernières décennies, le secteur de la construction a vu le déploiement de l'approche numérique de la modélisation des données du bâtiment, Building Information Modeling (BIM). Cette approche consiste à utiliser un modèle numérique multidimensionnel pour documenter et simuler la conception, la construction et l'exploitation d'un actif bâti. Parmi les différentes utilisations du BIM ─ conception assistée par ordinateur des bâtiments, visualisation 3D des modèles, gestion et coordination BIM, planification BIM 4D, estimation des coûts BIM 5D, etc. ─ la vérification des modèles est l'une des utilisations les plus pertinentes. De nombreuses études ont porté sur la coordination BIM et sur le degré d'adoption du BIM au sein des entreprises (meilleures pratiques, barrières à l'adoption, etc.). Néanmoins, peu d'articles traitent de la vérification des modèles numériques.

Pendant longtemps, la vérification des maquettes numériques s'est faite manuellement; le processus était long et fastidieux. Plusieurs aspects des normes de construction sont soumis à vérification (acoustique, insonorisation, thermique, isolation, sécurité incendie, résistance structurelle aux vibrations, aux chocs et aux tremblements de terre entre autres). Depuis le développement des outils BIM, cette vérification peut être effectuée numériquement : c'est ce que l'on appelle la vérification de modèle basée sur le BIM, en anglais *BIM-based model checking (BMC)*. Le gain de temps est important lorsque le modèle est composé d'un grand nombre d'éléments et d'un grand volume de données. Hjelseth y a consacré un chapitre entier (Issa & Olbina, 2015). D'autres utilisent le terme de vérification automatisée de la conformité au code, *code compliance checking*, lorsqu'un outil de validation du code est utilisé pour vérifier les paramètres d'un modèle conformément à un code spécifique (Code de la construction, etc.).

Appliqué à l'étape de vérification du modèle, le BIM peut augmenter la qualité de la conception en affichant le degré d'intégration entre les composants, en détectant les collisions *clash-detection* et en vérifiant les lignes de préfabrication des connexions (Ben Mahmoud, Lehoux, Blanchet, & Cloutier, 2022) par exemple. Hjelseth présente le développement actuel et le potentiel du BMC (Hjelseth, 2015). Son utilisation serait l'un des indicateurs de maturité du BIM et l'auteur déclare que l'interopérabilité doit être améliorée. La détection numérique des collisions facilite la vérification de la qualité des maquettes. Le BMC devient intéressant lorsqu'une grande quantité d'éléments est à manipuler. La détection des collisions d'aujourd'hui semble être trop grossière et pas assez précise. Certains déplorent la mauvaise qualité des modèles qui empêche un bon processus de vérification numérique. Ainsi, un problème majeur est identifié : si un modèle n'est pas suffisamment cohérent et si la qualité de l'information est trop médiocre, la vérification du modèle numérique ne peut pas être effectuée.

Dans une étude théorique, Hjelseth propose également les quatre types de contrôle suivants en fonction de leur nature de résultat (Hjelseth, 2016) :

- Validation checking : Cette vérification consiste en une comparaison du modèle selon des critères prédéfinis. Le résultat en sortie est : Réussite, Échec ou Non vérifié.
- Model content checking : Cette vérification consiste à examiner automatiquement le modèle BIM dans un but spécifique (utilisation de COBie). Le résultat en sortie est : Identifié ou Non identifié.
- Smart object checking : Cette vérification porte sur l'intégration et l'adaptation. Une proposition d'objets adaptés est faite en fonction de leur environnement. L'objet lui-même observe son environnement et s'y adapte automatiquement en suivant des règles de comportement ou des algorithmes intégrés. Le résultat en sortie est un objet adapté ou bien un modèle modifié.
- Design option checking : Cette vérification concerne l'orientation. Des propositions, des conseils et des options sont suggérés pour guider le concepteur. C'est l'idée d'un système de connaissances pour sélectionner des solutions pertinentes. Pour l'instant, "les solutions logicielles spécialisées ne sont pas connues". Le concept de vérification des options de conception vise à guider le concepteur pour qu'il envisage un plus large éventail de solutions réalistes. Ce type de vérification est étroitement lié aux meilleures

pratiques et aux systèmes d'aide à la décision, mais jusqu'à présent, ce concept n'a pas été mis en œuvre dans le secteur de la construction.

Dans la version 3.0 du BIM Project Execution Planning Guide, Messner propose quatre manières de réviser le modèle de conception (Messner, Anumaba, Dubler, & Goodman, s.d.). Le contrôle visuel permet de s'assurer qu'il n'y a pas de composants de modèle non souhaités et que l'intention de conception a été respectée à l'aide du logiciel de navigation. Le contrôle des interférences détecte les problèmes dans le modèle lorsque deux éléments de construction s'opposent à l'aide d'un logiciel de détection des conflits. Le contrôle des normes garantit que le modèle est conforme aux normes convenues par l'équipe. Enfin, la validation des éléments garantit que l'ensemble de données ne contient pas d'éléments non définis ou mal définis. Cette classification est destinée à la vérification de la qualité du modèle (Messner et al., s.d.). Elle évalue la qualité de la conception : la qualité de la maquette est-elle suffisante pour faire fonctionner correctement le modèle ? Mais ces critères n'évaluent pas la constructibilité du modèle ou sa conformité aux règles de construction.

Hjelseth a proposé cinq niveaux de maturité du BMC (Hjelseth, 2015) selon les études de Succar publiées en 2009 (Succar, 2009).

1. Vérification de la détection des conflits
2. Vérification du modèle ajusté
3. Vérification de l'objectif spécifique
4. Vérification du modèle intégré
5. Vérification omniprésente du modèle

Les niveaux suggèrent que le BMC offre de multiples options de vérification, de la détection des collisions à la vérification avancée de la conformité du code. Cette catégorisation par niveaux suppose implicitement qu'une vérification de niveau N+1 inclut les propriétés du niveau N : cela doit être vérifié. Hjelseth a proposé une matrice à deux axes pour décrire chaque niveau (Hjelseth, 2015). Il considère que la complexité de la vérification du modèle à l'aide du

BIM repose sur deux éléments : la complexité des règles numériques et la qualité des données numériques du modèle. Si la première dépend de ce que l'on veut vérifier, la seconde dépend du niveau de développement, *level of development* (*LOD)*, du modèle utilisé sur lequel on veut effectuer la vérification. Il est évident que ces paramètres peuvent changer pour chaque projet. Cette classification nous aide à évaluer les possibilités de contrôle de chaque outil.

L'importance de la qualité des informations du modèle a été soulignée à plusieurs reprises. La taxonomie pour la classification des niveaux de BMC est basée sur deux critères (taxa) (Issa & Olbina, 2015) : l'exigence du contenu de l'information dans le fichier BIM ("le I dans le BIM") et la complexité dans le jeu de règles (intelligence des règles).

La vérification de la conformité au code fait partie de la vérification des modèles. Ce type de vérification consiste à vérifier si le modèle est conforme aux clauses d’un code. Plusieurs articles proposent des classifications des clauses du code à vérifier en fonction de leur nature. Comment décrypter un énoncé de règles à vérifier pour les automatiser ? Aussi, le défi actuel consiste à convertir les règles de conception et les réglementations en règles numériques (règles interprétables par la machine). Certaines dispositions peuvent être transcrites, d'autres non. Dans la littérature, de nombreuses études se concentrent sur cette question.

Pour étudier leur automatisation potentielle, il existe des classifications des clauses de code dans la littérature spécialisée. Malsane et al. ont travaillé dans le contexte du Royaume-Uni où les réglementations évoluent rapidement (Malsane, Matthews, Lockley, Love, & Greenwood, 2015). L'automatisation de cette vérification repose sur le format commun d'interopérabilité IFC. Si les logiciels et les outils numériques sont génériques et internationaux, les réglementations et les codes sont quant à eux, spécifiques et locaux. Il différencie deux types de clauses : les clauses déclaratives (interprétables par ordinateur) et les clauses informatives (non interprétables, nécessitant une interprétation humaine) (Malsane et al., 2015). En 2018, Nawari propose une autre classification des clauses. Il distingue quatre types de règles (Nawari, 2018). Ces catégorisations permettent d'identifier les clauses pour lesquelles la vérification peut être automatisée :

- Clauses conditionnelles : Le texte des clauses est directement interprétable en un ensemble de règles formelles. Les caractéristiques typiques comprennent des règles avec des valeurs spécifiques.
- Clauses de contenu : Le contenu des clauses ne peut pas être transformé en expressions VRAI ou FAUX. Ces clauses sont normalement utilisées pour les descriptions et les définitions.
- Clauses ambiguës : Le contenu des clauses est subjectif. Elles comprennent généralement des mots tels que approximativement, à peu près, relativement, proche de, loin de, peut-être, etc.
- Clauses dépendantes : Certaines clauses dépendent d'autres clauses. Cela signifie que certaines dispositions ne conviennent qu'à une condition particulière.

Pour réaliser une vérification automatisée de la conception des bâtiments à l'aide du BIM dans la phase de conception initiale, il est nécessaire de passer par un processus d'élaboration et de "fabrication" de règles appropriées, afin qu'elles soient lisibles par l'ordinateur (Kim, Lee, Shin, & Choi, 2017). Aujourd'hui, la transcription des règles de conception en code interprétable par une machine est réalisée par des humains. Certains processus utilisent un algorithme d'exécution compatible IFC en code dur pour l'automatiser. D'autres s'appuient sur une interprétation logique basée sur les aspects syntaxiques, lexicaux et sémantiques des règles.

Actuellement, cette revue de conception est réalisée à l'aide d'un processus automatique et semi-automatique basé sur des règles codées en dur (Nawari, 2019). Elles sont adaptées à des applications spécifiques. Mais on peut relever certains inconvénients. Les règles basées sur un code en dur sont difficiles à modifier, il manque un cadre généralisé pour des modèles de régulation adaptables et transposables à d'autres domaines d'ingénierie. L'auteur propose un cadre adaptatif généralisé au format standard IFC qui permet d'automatiser le processus de vérification de la conformité au code afin d'atteindre l'efficacité, la qualité et la rentabilité de la conception. L'auteur se concentre sur le développement d'un contexte théorique pour transformer le code en un modèle lisible et interprétable par ordinateur.

En utilisant les données de la loi coréenne sur la construction, Kim et al. ont travaillé sur la transformation des clauses en un code interprétable par une machine (Kim et al., 2017). KBim Visual Language (KBVL) est un langage visuel qui permet de générer du code automatiquement après avoir identifié et traité chaque élément constitutif d'un énoncé de clause (propriété relative, verbe, relation, etc.) à partir d'un code. Le code généré automatiquement est ensuite exporté dans un fichier avec un ensemble de règles vers un logiciel de vérification des règles. Cette méthode sépare les processus d'élaboration et de vérification des règles. La possibilité de créer et de modifier des règles à l'aide d'un langage visuel permettra aux règles d'évoluer avec les réglementations, en particulier pour les bâtiments en bois où les réglementations changeront et deviendront plus précises à l'avenir.

Le travail de Preidel a consisté à analyser deux approches d'automatisation (Preidel & Borrmann, 2015) : l'une basée sur le Visual Code Checking Language et l'autre semi-automatisée appliquée au code de sécurité incendie allemand. Depuis 1995, Singapour effectue des vérifications avec l'outil CORENET, qui utilise la bibliothèque FORNAX codée en dur.

En 2009, Eastman et al. ont défini pour la première fois quatre étapes qui structurent la vérification des règles (Eastman, Lee, Jeong, & Lee, 2009) : (1) l'interprétation des règles, (2) la préparation du modèle de construction, (3) la phase d'exécution des règles et (4) la communication des résultats de la vérification. Quelques années plus tard, Nawari (Nawari, 2018) et Preidel (Preidel & Borrmann, 2015) réutilisent ce cadre. Ils insistent tous sur l'importance de la phase d'élaboration, de " fabrication " de règles appropriées pour qu'elles soient lisibles par l'ordinateur. Mais quelques défis concernant le BMC subsistent (Preidel & Borrmann, 2015). Lorsque le processus manque de transparence et de visibilité pour l'utilisateur, il est difficile de comprendre et d'appliquer les règles.

Récemment, Kincelova a travaillé sur l'utilisation de la BIM pour améliorer l'intégration de la protection incendie dans les bâtiments de grande hauteur en bois (Kincelova, Boton, Blanchet, & Dagenais, 2020). L'auteur a concentré son travail sur l'intégration de la sécurité incendie passive dans le processus de conception à l'aide d'outils BIM. Une méthode cohérente abordant les questions de conception en sécurité incendie a été proposée. De plus, pour comparer les possibilités de vérification automatisée de la conformité, Kincelova a évalué huit outils de vérification différents, en termes de vérification de la conformité au code appliquée à la protection incendie (Kincelova, Boton, Blanchet, & Dagenais, 2019). Leurs résultats suggèrent que les solutions de vérification de code existantes ne parviennent pas encore à répondre aux défis de la protection incendie, car celle-ci a des besoins spécifiques en termes de modélisation.

1.3 Conclusion de la revue de littérature

Aujourd'hui, il est nécessaire d'utiliser la BIM pour les projets de construction, et en particulier pour les projets de construction en bois massif. Même si certains outils numériques sont déjà utilisés dans l'ensemble du processus, la vérification de modèle basé sur le BIM (BMC) est utilisée dans très peu de projets de construction pour vérifier les modèles numériques. Aussi pour comprendre l’avancement des pratiques et l’utilisation des ressources de vérification des modèles numériques, il faut bien connaître les enjeux des acteurs majeurs d’un projet de construction.

La littérature a montré que, en théorie, le BMC a un grand potentiel pour accélérer l'étape de vérification d'un modèle. En effet, lorsque toutes les conditions d'application sont réunies, le BIM offre un potentiel impressionnant de gains de productivité grâce à la numérisation. Jusqu'à présent, cette pratique de vérification numérique a été étudiée théoriquement sous certains angles, mais il n'existe pas de méthode générale et systématique dédiée à sa mise en œuvre. Aussi, on déplore un fossé entre la recherche théorique et l'utilisation pratique des outils de vérification. Il manque également des études sur les différents besoins de vérification selon les différents projets de construction. Par exemple, un projet d'infrastructure aura des besoins de vérification différents de ceux d'une construction modulaire préfabriquée. Sous certaines conditions, le processus de BMC promet de bien considérer et de prendre en compte les défis du bois massif. Dans notre travail de recherche, nous nous concentrons à étudier la manière d'implémenter correctement le BMC et de prendre en compte les spécificités du bois massif.

CHAPITRE 2

DÉMARCHE ET ORGANISATION DU TRAVAIL

Le présent chapitre a pour but de présenter le cadre qui va permettre de répondre à la problématique présentée précédemment. L'intention de recherche et les objectifs ─ principal et spécifiques ─ seront décrits, puis la méthodologie de travail qui nous a permis d'atteindre ces objectifs. Enfin, le dernier paragraphe décrira les publications d'articles liées à cette recherche.

2.1 Intention de recherche

Ce travail de recherche a l'intention très générale de promouvoir le choix du bois massif comme matériau pour les nouvelles constructions au Québec. Comme nous l'avons vu, cette nouvelle technologie présente de nombreux avantages, notamment en termes de durabilité. Plus spécifiquement, nous souhaitons faciliter l'étape d'étude de conformité d'un modèle numérique pour une future construction en bois massif. En premier lieu, nous avons étudié le processus de vérification de modèles numériques d'une manière générale, puis en tenant compte des particularités du bois massif, nous avons l'intention de réaliser quelques études de cas de vérification de modèles de bois de construction.

2.2 Objectifs spécifiques

L'objectif principal de la recherche est de caractériser le processus d'étude de conformité à diverses exigences, basée sur le BIM des modèles numériques, en particulier pour les constructions en bois massif. Pour ce faire, les objectifs spécifiques sont les suivants :

- proposer une méthode générale, supportée par des outils, qui synthétise les étapes du processus de vérification automatisée de modèle basée sur le BIM ;
- mener une étude comparative de plusieurs logiciels dédiés à la vérification automatisée de modèle;

- procéder à trois études de conformité de modèles pour établir la preuve de concept de la méthode proposée.

Ces objectifs ont été atteints par la méthodologie de recherche formalisée ci-dessous.

2.3 Méthodologie et approche de recherche

Pour mener à bien ce travail de recherche, nous avons suivi trois étapes distinctes : compréhension des enjeux, formalisation de la méthode et validation de la méthode.

2.3.1 Compréhension des enjeux : entrevue avec trois acteurs de l'industrie du bois massif

La première étape du processus de recherche a consisté à comprendre les enjeux soulevés par notre problématique: d'une part, il existe des défis concernant l'adoption du bois massif comme nouveau matériau dans l'industrie AEC, d'autre part, il existe des défis sous-jacents au processus de vérification des modèles et la numérisation de cette tâche. Nous avons rencontré des industriels du milieu de la construction en bois massif. Au début, nous nous sommes beaucoup intéressés au sujet de la construction hors site, de la notion de DfMA et des questions de préfabrication en usine pour les bâtiments. De nombreux rapports sur l'adoption du bois massif ont été consultés. Il existe de nombreux de rapports d'entreprises ou de guides proposés sur le sujet du bois massif dans le secteur de la construction, mais il faut noter que peu d'articles ou d'études scientifiques l'étudient rigoureusement et scientifiquement. Quelques rapports de recherche se concentrent spécifiquement sur le BIM appliqué pour des projets en bois massif. Aussi, il a été intéressant de s'attarder sur les grandes structures en bois massif construites récemment à l'international. La plupart d'entre elles ont été très médiatisées : pour n'en citer que trois : Brocks Common, une résidence étudiante à Vancouver ; HoHo Vienna, un bâtiment de 84 mètres de haut en Autriche, et Mjøstårnet en Norvège, le plus haut bâtiment en CLT à sa construction en 2019. Mais ces rapports étaient surtout une description des travaux, une présentation du CLT et du bois massif pour le grand public. Les normes canadiennes, les codes de construction et les normes sur les constructions en bois ont aussi été consulté.

Nous avons eu l'occasion de réaliser des entrevues avec des acteurs de l'industrie du bois massif. Au total, nous avons réalisé trois rencontres. D’abord nous avons rencontré deux ingénieurs d'une entreprise de génie conseil pour les constructions en bois, dont l'expertise est la fabrication de CLT. L’entrevue n°1 était virtuelle et a duré 1 heure. Une semaine après, nous avons refait une entrevue, en présentielle d’une durée de 2 heures. Nous nous sommes aussi entretenus avec une architecte qui a travaillé à la conception d'un complexe résidentiel en CLT construit à Montréal. L’entrevue était virtuelle et a duré 2 heures. Nous avons évoqué les problèmes de collaboration entre les ingénieurs et l'architecte, les sous-traitants MEP et le concepteur-fournisseur de bois massif pour un projet de construction à Montréal. Ils ont parlé des particularités de fabrication en usine, de la pertinence de travailler avec le BIM pour le bois massif et des difficultés liées à la non-standardisation de ce nouveau matériau. La discussion avec l’architecte a porté sur les difficultés de conception à prendre en compte avec le bois massif et le BIM.

2.3.2 Formalisation de la méthode : Élaboration par itération du cadre de travail pour étudier la conformité d’un modèle numérique

Une fois l’état de l’art du sujet effectué, nous avons formalisé notre solution, c'est-à-dire la méthode globale supportée par des outils. Il s’agit d’une méthode en cinq étapes, permettant d’étudier la conformité à une exigence avec plusieurs logiciels de vérifications et sur plusieurs modèles numériques. Le processus de construction de la méthode était itératif : nous avons tout d’abord effectué des vérifications simples avec des modèles quelconques, il a ensuite été facile de caractériser chacune des étapes. Puis des itérations ont permis, en ré-effectuant des tests d’améliorer la méthode. Les outils supportant la méthode ont aussi été vérifiés et contrôlés par itération. Nous les avons utilisé pour mener nos vérifications puis nous les avons améliorés chacun individuellement.

2.3.3 Validation de la méthode : Preuve de concept à travers trois études de cas

Dans la troisième étape, nous avons effectué trois vérifications sur des maquettes numériques de bâtiments en bois massif. Le but étant d'appliquer pas à pas la méthode globale proposée, avec les différents outils pour la mettre en place, puis de conclure quant au concept avancé.

Nous avons donc suivi la méthode proposée et noté les résultats à chaque étape. Nous avons manipulé trois modèles : un modèle éducatif standard, la maquette architecturale d'un complexe de condominiums en bois massif construit à Montréal au début des années 2010 et le modèle MEP associé à ce même projet. Nous avons reçu les autorisations des entreprises pour utiliser leurs modèles. Nous avons choisi les logiciels suivants : Revit, son plugin Dynamo, Navisworks et Solibri Model Checker. Ce sont des logiciels de conception et de vérifications BIM. Pour l'étude de cas, nous avons choisi trois vérifications de nature, provenance et de complexité différentes. Elles sont toutes liées aux aspects fondamentaux de la conception. La première est une vérification géométrique simple proposée par les industriels du bois massif : la portée des dalles de CLT ne doit pas excéder 18 fois son épaisseur. La deuxième est une vérification de positionnement complexe émise par les ingénieurs et architectes d'un même projet : les percements pour conduits MEP doivent être correctement positionnés. Enfin, nous avons suggéré la troisième vérification qui est de type quantitative et relativement simple : le même panneau de CLT doit apparaître un minimum de 20 fois dans le modèle. Après avoir effectué ces différentes vérifications de modèles, on note les difficultés rencontrées.

2.3.4 Présentation des articles

L'étape de comparaison des performances de plusieurs logiciels de vérification fait l'objet d'un article de conférence intitulé *Comparative analyses of four BIM-based compliance checking tools* (ANNEXE I). Le travail a montré que les quatre logiciels de vérifications BIM étudiés ─ Dynamo, Grasshopper, Navisworks and Solibri Model Checker ─ se complètent les uns aux autres. Ils permettent tous de procéder à une vérification automatisée des règles, mais de manière différente. Les outils de vérifications fonctionnant en programmation visuelle apportent une flexibilité dans la création de règles à vérifier; les outils ayant des pre-rulesets sont eux très performants dans une vérification bien précise. Cette étude comparative nous a permis de sélectionner adéquatement l'outil pour mener les études de cas.

Dans l'article de journal intitulé *BIM-based checking method for the mass-timber industry* (CHAPITRE 3) est présentée la méthode de vérification, puis son application au contexte de l'industrie du bois massif. Cette méthode comporte plusieurs étapes en partant de la spécification des besoins de vérification jusqu'à l'analyse des résultats sur de conformité ou non du modèle. La méthode, par la suite testée sur trois études de cas bois massif, démontre l'applicabilité de la méthode mais aussi les difficultés rencontrées et ses limites relatives.

CHAPITRE 3

BIM-BASED CHECKING METHOD FOR THE MASS-TIMBER INDUSTRY

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3.1 Abstract

Since the 90's, mass-timber constructions are becoming more and more popular. This type of construction has characteristics that are ideal for incorporating Building Information Modeling (BIM). Mass timber structure implies off-site prefabrication at the factory, which generates modeling specificities. Although digitalization and BIM are becoming more and more common, and some studies have focused on BIM for mass timber construction, none of them focus on mod-el-checking for mass timber construction. In construction projects, there is still no general method that synthesizes the possibilities offered by BIM-based model checking in general, and research on the conformity study of mass timber models in particular is almost non-existant. Our research objective is to provide a general step-by-step method summarizing the process of model compliance study with dedicated tools. To conduct this work, we first solidified our understooding of the problem by interviewing professionals from the mass timber construction industry. Next, we developed our method iteratively, supported by tools, and then validated it with three mod-el-checking case studies. This method consists of five steps: checking the need specifications, digital environment implementation, requirement deciphering, calculation, and compliance results' analysis. We then applied our method in three case studies. The results of the case studies are mixed: some audits were successful, others were not, because barriers to auditing were en-countered (missing information, impossible interpretation of datas in the model proprerties, etc.). The obstacles encountered show that, to be efficient, BIM must be conducted on high-quality models, which is not often the case in real-life situations.

Keywords: Building Information Modeling, Mass timber, Building codes, Code compliance checking, Rule checking, Model-checking, Design assessment, Digital mockup, Methodology.

3.2 Introduction

With the current development of digital tools for the architecture, engineering, and construction (AEC) industry, it is becoming more and more common to work with a 3D digital model to design, build and operate a building. Building Information Modeling (BIM) is the main digital approach to construction projects: it allows the centralization of data, the planning of the work, and the coordination of a project around a single digital model. The compliance study of digital models is therefore an important step in designing and validating a digital working model. There are already processes in place to ensure compliance with the building code. But there are other requirements that need to be addressed as well. While performing such verification by hand is time-consuming, BIM tools would allow the process to be automated and extend it to a large number of models. A digital model can be checked in many ways, and several tools and software dedicated to model verification are available. Certainly, numerous studies are dealing with geometry clashes utilizing the scan-to-BIM method. But other types of checking exist and it's not clear which BIM checking tool is most appropriate for each different type of checking. For designers and actors in the AEC industry working in the design phase, it would indeed be helpful to know which type of verification is possible with which tool, and which verification type is automatable or not.

Certain categories of projects require the use of BIM more than others, and there-fore need to be able to correctly conduct model conformity studies. This is the case for mass timber constructions, whose new technology (off-site construction, new non-standardized materials, etc.) implies particular verifications. The objective of this study is to present a five-step method for the conformity assessment of digital models, and to then perform a verification application of a digital model of a mass timber building.

After presenting some related works in the next section, we introduce an over-view of the suggested method, based on our interviews of some professionals in the field. Each of the five steps are detailed: verifying the specifications, digital environment implementation, requirement deciphering, calculation and how to analyze compliance based on the results. The five-step method is applied to three case studies in a mass timber building context as proof of concept in the fourth section. For these applications, we detail precisely the context in which we perform the checking. A discussion and a conclusion about the research results conclude the paper, including the limits of this method and suggestions for future work.

3.3 Related works

3.3.1 Mass timber construction

The timber industry is considerable in Canada. In 2020, the wood product industry contributed 6% to revenue from goods manufactured in the country of a value of $635.1 billion (S. C. Government of Canada, 2022). In Quebec in particular, forests cover more than half of the territory or more than 900,000 km² (Ressources naturelles et Forêts, 2023). However, it is only in 2012 that the technology of mass timber construction appeared in Canada, while it took place in the 90s in Europe. In 2019, the production of cross-laminated (CLT) panels was 1.44 million m3 worldwide; according to the United Nations, this volume will double by 2025 (United Nations, 2021). Mass timber construction is a promising technology both structurally and sustainably. The objective of this subsection is to present this material, and the resulting model-checking requirements.

Two types of wood structures are identified in the literature: light frame and mass timber. Mass timber structures are characterized by the use of large panels and columns of pre-assembled wood. They are laminated from smaller boards or lamella into larger structural components. Mass timber constructions benefit from the enhanced performance of this manufacturing technology (rigidity, lightness), in addition to the performance due to the use of wood as a material (durability, insulation, sustainability and aesthetics).

The recent development of mass timber construction has made it possible to in-crease the number of floors in wood-framed buildings because the bi-directionality of CLT panels provides stability and rigidity similar to that of reinforced concrete. While light frame structures are entirely built on-site, mass timber constructions are prefabricated off-site and then assembled. In this section, offsite construction particularities described, followed by mass timber particularities, to better understand the main challenges involved in this type of project.

Offsite construction is a type of construction in which pieces of a building are manufactured at the plant and then assembled on site. Digitalization and digital tools offer a new approach to modular and offsite projects (McKinsey&Compagny, 2019). They must be designed while considering the manufacturing conditions at a plant. This aspect directly influences has the design process. We categorize these factors into three parts: prefabrication at the plant, non-adapted regulations and the transport of prefabricated elements.

- **Prefabrication at the plant**. Mass production at a plant is cost-effective (Smith & Quale, 2017). The controlled environment (temperature, humidity, electricity, etc.) allows the manufacturing process to be automated, ensuring a faster and more risk-free manufacturing process (McKinsey&Compagny, 2019). This automation involves the industrialization of the manufacturing process and thus the standardization of elements in high quantities. Prefabrication is relevant only with the following materials: steel, aluminum, and wood. In this context, concrete is not a suitable material.

- **Non-adapted regulations**. The current codes and regulations do not distinguish offsite construction from classic construction in situ (Wilson, 2020).
- **Transport of prefabricated elements**. Building parts manufactured at a plant must be transported to the construction site. In addition to the transport, the assembly and storage must be considered. Those stages limit the total volume and weight that can be accommodated. Modular parts have to be designed such that as little empty space as possible will be transported. To optimize the elements' storage duration, an optimal onsite delivery frequency must be determined. Thus, the whole transport process of modular elements has to be considered during the design phase. This aspect is referred to as the notion of DfMA (Design for Manufacturing and Assembly): prefabricated modules are designed to make the manufacturing, the assembly, and the delivery as easy as possible.

Mass timber construction requires the prefabrication of mass timber elements like CLT panels and glulam posts and beams at the plant. Furthermore, mass timber as a specific material technology has its unique particularities. These aspects influence the design of the building, therefore it implies constraints during the conformity study of the model. We classify them into three categories: offsite prefabrication, wood as mass timber, and the related regulations.

- **Offsite prefabrication.** Due to the manufacturing process of mass timber, such constructions imply offsite construction particularities. Also, the design must consider the manufacturing capabilities of the CLT plant: the facilities, the production infrastructure, the storage capacity, the production volume, etc. The equipment and the infrastructure at the plant limit prefabricated part's dimensions. While a building is usually a customer-oriented prototype, elements prefabricated at the factory are product-oriented.
- **Wood as mass timber**. Certain requirements linked to the use of mass timber as a material must be considered. The manufacturing process of CLT panels by layers implies specific structural resistance. The ideal ratio between the span and the panel thickness is recommended by the manufacturer.

- **Related regulations**. Timber building is bound by regulations and codes, with specific codes for mass timber building. These regulations are presented in the next paragraph. While some European and North American countries have adjusted their building codes to allow the construction of mid-rise and in some cases high-rise buildings out of wood, many others still need to adopt appropriate regulations (Churkina et al., 2020).

Like all buildings, mass timber ones must be built in compliance with current regulations. Our literature review has revealed that in addition to common building codes, some specific regulations concern wood and mass timber construction. The norm CSA086 from the National Building Code of Canada specifies the calculation rules for wooden structures (Commission canadienne des codes du bâtiment et de prévention des incendies, 2022). Standard ANSI/APA PRG 320 is dedicated to CLT construction (American National Standards Institute, 2018), and the norm CSA O122 to glulam (CSA Group, 2016). Pelletier et al. focus on mass timber encapsulated buildings of up to 12 stories (Pelletier et al., 2022). The domain expert Karacabeyli has proposed a CLT handbook with FP Innovations (Karacabeyli & Gagnon, 2019) and a guide for tall wood buildings in Canada (Karacabeyli & Lum, 2022). However, the current codes do not distinguish between combustible construction systems, i.e., light-frame construction, column and beam systems, structurally-engineered wood, glulam, cross-laminated wood, and hybrid construction (Pelletier et al., 2022).

These codes suggest various mass timber requirements that impact the design. The norm ANSI/APA PRG 320 (American National Standards Institute, 2018) defines geometric requirements for CLT panels. The maximal thickness is 20 inches (508mm), and the dimensional tolerances for the length, width, and thickness of a CLT panel are also specified. The ideal thickness of the lamellas is stated as between 5/8 of an inche (16mm) and 2 inches (51mm). Karacabeyli's guide (Karacabeyli & Lum, 2022) proposes an objective-based code (as opposed to a performance-based code). He advocates maximum use of prefabrication to reduce costs and increase construction efficiency. To optimize the vertical loads, he recommends having as many large spans as possible in the upper floors, i.e. few beams. The available thickness of the panel determines the possible span and its performance against fire.

These specificities impact a building's design, and thus on its digital model. Several issues must be considered in the modeling. As noted earlier, transport, logistics, delivery, storage, and assembly are some of the specific stakes to consider. The transport stage limits the size (and weight) of prefabricated modules. It is also necessary to take into account road transport regulations, if there will be a need for exceptional convoys, authorizations, etc. A maximum width of 3.5m is standard for road transport (Smith & Quale, 2017). For classic 3D modular construction, it is important to not transport or store too much vacuum, but with prefabricated mass timber 2D panels, this is not a major consideration. The repeatability of design is also important to consider, because construction off-site at the factory is only relevant for standardized buildings (residential buildings, dormitories, hotels, hospitals, etc.) (McKinsey&Compagny, 2019). The more repetitive a building design is, the more attractive the mass timber option becomes.

Thus, a building must be thought of from the perspective of prefabrication from the design state. Unlike conventional constructions, it is necessary to work in collabo-ration with each trade from the beginning, as modeling decisions must be made much earlier and no rework is possible. Offsite projects imply a high level of integration: collaboration between designers and manufacturers, the definition of roles and responsibilities, and the use of a collaborative platform for the model (Wilson, 2020). To achieve this level of collaboration, a collaborative platform such as a BIM tool is required. Moreover, the design-bid-build approach is not suitable for prefabrication; instead, the IPD (Integration Project Delivery) approach fits better in mass timber construction. BIM and offsite construction are closely related (Alfieri et al., 2020).

The digital approach benefits each stage of mass timber construction. Computer-aided design (CAD) modeling software and parametric design in visual programming tools are used at the modeling stage. For the prefabrication at the plant, 2D industrial drawings of prefabricated parts can be extracted from the 3D digital model directly to CNC (Computer Numerical Control) machines. Digital planning management is key to the delivery of just-in-time modules to limit travel and optimize storage. In particular, BIM offers the possibility to federate digital models (architectural, structural, and mechanical, electrical and plumbing (MEP), to proceed with time simulation (BIM 4D), and to perform comparative analyses (e.g., costs, GHG emissions). The BIM offers the advantage of centralization around the same model, thereby allowing model checking, including the ability to study its compliance with current building codes and regulations, and with offsite plant manufacturing capabilities. A few companies utilize BIM in the wooden construction manufacturing process, i.e., Sieveke GmbH and Wolf System/Haus both from Germany.

The second section of the literature review presents the state-of-the-art of digital model checking based on the use of BIM.

3.3.2 BIM-based model checking

In the last few decades, the construction industry has seen the deployment of the digital BIM approach. This approach involves using a multidimensional digital model to document and simulate the design, construction, and operation of a built asset. Several ISO standards regulate BIM implementation, in particular ISO 19650. This international standard concerns BIM processes and exposes the principles to be applied for the modeling of the data of a construction project and the management of the information during the life cycle of buildings. Among the various uses of BIM ─ computer-aided design of buildings, 3D visualization of models, BIM management and coordination, BIM 4D planning, quantity takeoff, BIM 5D cost estimation, etc. ─ model checking is one of its most relevant uses. While many studies have focused on BIM coordination and the degree of BIM adoption within companies (best practices, barriers to adoption, etc.), few articles have covered digital model verification.

Since their introduction, the verification of digital mock-ups has almost always been done manually, a long and tedious process. Several aspects of building standards are subject to verification (acoustics, soundproofing, thermal quality, insulation, fire safety, structural resistance to vibrations, shocks, and earthquakes, among others). Since the development of BIM tools, it has been possible to perform this verification digitally, with a process called BIM-based Model Checking (BMC) (Hjelseth, 2015). Time-saving is especially important when a model is composed of a large number of elements and a large volume of data. Hjelseth devoted an entire chapter to this situation (Issa & Olbina, 2015). Others use the term automatic code compliance checking when a code validation tool is used to check the parameters of a model according to a specific code (Building Code, etc.).

Applied to the model-checking stage, BIM can increase the quality of the design by displaying the degree of integration between components, detecting potential collisions, and checking the prefabrication lines of connections (Ben Mahmoud et al., 2022), for example. Hjelseth presents the current developments and the potential in BMC. Its use can be one of the BIM maturity indicators, and Hjelseth declares that interoperability must be improved for the use of BMC to be implemented more broadly. Digital clash detection greatly improves the traditional quality assessment of drawings; BMC becomes a worthwhile option when a huge amount of elements must be managed. However, digital clash detection is still too approximate and lacks accuracy. The poor quality of current models hinders the development of a good digital checking process. This situation highlights a major issue: if a model is not consistent enough and if it has poor information quality, digital model checking cannot be done.

In a theoretical study, Hjelseth suggests the following four types of checking according to the nature of their outcomes (Hjelseth, 2016):

- Validation checking compares the model with predefined criteria. The outcome can be: “Pass,” “Fail,” or “Not checked”.

- Model content checking examines the BIM model automatically for a specific purpose (e.g., for the use of COBie: Construction Operations Building information exchange). The outcome has two options: identified or not identified.
- Smart object checking evaluates a model's integration and adaptation. A proposal of an adapted object is made according to its environment. The object itself observes its environment and automatically adapts to it by following embedded behavior rules or algorithms. The outcome is an adapted object or a modified model.

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Version 3.0 of the BIM Project Execution Planning Guide suggests four steps to review a design model (Messner et al., s.d.).

- A Visual Check ensures that there are no unintended model components and that the design intent has been followed by using navigation software.
- An Interference Check detects problems in the model where two building components are clashing, identified by conflict detection software.
- A Standards Check ensures that the model is to the standards agreed upon by the team.
- Element Validation ensures that the dataset has no undefined or incorrectly defined elements.

This classification process is intended for model quality checking (Messner et al., s.d.). It evaluates the design quality: is the mockup quality sufficient to properly operate the model? However, these criteria do not evaluate the model constructability or its built regulations' compliance.

Others have proposed levels of BMC; the five levels of BMC maturity proposed by Hjelseth (Hjelseth, 2015) according to Succar studies published in 2009 (Succar, 2009) are:

1. Clash detection checking;
2. Adjusted model checking;
3. Specific purpose checking;
4. Integrated model checking; and
5. Pervasive model checking.

The various levels indicate that BMC offers multiple checking options from clash detection to advanced code compliance verification. Such multi-level categorization implies that level n + 1 necessarily includes level n, but this must be verified. Heljseth describes these levels in a 2-axis matrix (Hjelseth, 2015). This classification based on those two axes, digital rule complexity and the quality of the model's digital data/information, suggests that BMC levels are directly dependent upon these two aspects. If the former depends upon what you want to verify, the latter depends upon the model on which you want to do the checking. It is obvious that for each project those parameters may change. This classification helps us to assess the checking possibilities of each tool.

The importance of model information quality has been highlighted repeatedly. The taxonomy for the classification of BMC level is based on two criteria (taxa) (Issa & Olbina, 2015): the requirement of the content of information in the BIM file ("the I in the BIM"), and the complexity in the ruleset (intelligence of rules).

Code compliance checking is a part of model checking. This type of verification evaluates how completely a model is compliant with code clauses. Several articles propose code clause classifications to be verified according to their nature, including how to decipher a statement of rules in order to automate them. One challenge is how to convert design rules and regulations into digital rules (computable rules). While some clauses' provisions can be transformed, some others cannot.

Classifications of code clauses have been developed as part of evaluating their potential automation. Malsane et al. has worked in the context of the UK, where regulations are evolving rapidly (Malsane et al., 2015). The automation of their proposed verification approach is centered around the common interoperability of the Industry Foundation Classes (IFC) formats. While software and digital tools are generic and international, regulations and codes are specific and local. They differentiate two types of clauses, declarative (computer-interpretable) and informative (non-interpretable, requiring human interpretation) (Malsane et al., 2015). In 2018, Nawari suggested another type of clause classification. He distinguished four types of clauses (Nawari, 2018) that effectively classify the provisions of any given building code into four main categories (Nawari, 2018). These categorizations help to identify for which clauses the checking can be automatized.

- Conditional clauses: These can be interpreted directly from the textual document into a set of formal rules. Typical features include rules with specific values.
- Contents clauses: This type of clause cannot be transformed into TRUE or FALSE expressions. These clauses are normally utilized for descriptions and definitions.
- Ambiguous clauses: These clauses have subjective provisions. They normally include words such as: approximately, about, relatively, close to, far from, maybe, etc.
- Dependent clauses: Some clauses are dependent on others, which means some provisions are only suitable for a particular condition.

To perform an automated assessment of building design using BIM in the initial design phase, it is necessary to go through a process of elaborating and "manufacturing" appropriate rules so that they are computer readable (Kim et al., 2017). Transcribing design rules into machine-interpretable code is still done by humans, but some processes use an IFC-compatible execution algorithm in hard code to automate. Others rely on a logical interpretation based on the syntactic, lexical, and semantic aspects of the rules.

Currently, design review is done using both automatic and semi-automatic processes based on hard-coded rules (Nawari, 2019). While these are suitable for specific applications, there are some disadvantages: rules based on hard code are difficult to modify, there is no generalized framework for adaptable regulation models and so they are not transposable to other engineering domains. A generalized adaptive framework in the standard IFC format that allows automation of the code compliance verification process has been proposed to achieve efficiency, quality, and profitability of the design (Nawari, 2019). That work focuses on the development of a theoretical context of the framework to transform the code into a computer-readable model.

Using data from the Korea Building Act, Kim et al. worked on the transformation of clauses into machine-interpretable code (Kim et al., 2017). KBim Visual Language (KBVL) is a visual language that makes it possible to generate code automatically after identifying and processing each constituent element of a clause statement (relative property, verb, relation, etc) from a code. The automatically generated code is then exported in a ruleset file to a rule-checking software. This method separates the rule-making and rule-checking processes. The ability to create and modify rules with visual language will allow the rules to evolve with the regulations, specifically for wood buildings where regulations are changing and will become more precise in the future.

Preidel's work analyzes two automation approaches (Preidel & Borrmann, 2015): one based on Visual Code Checking Language, and a semi-automated approach applied to the German fire safety code. Since 1995, Singapore has been performing checks with the CORENET tool, which uses the hard-coded FORNAX library.

In 2009, Eastman et al. defined four stages that structure rule checking (Eastman et al., 2009): (1) rule interpretation, (2) building model preparation, (3) the rule execution phase, and (4) the reporting of the checking results. A few years later, Nawari (Nawari, 2018) and Preidel (Preidel & Borrmann, 2015) reused this framework. They all insist on the importance of the elaboration stage, of "manufacturing" appropriate rules so that they are readable by the computer. Some challenges regarding BMC remain (Preidel & Borrmann, 2015). When the process lacks transparency and visibility to the user, it is difficult to understand it. For legal reasons, someone must be responsible for compliance verification; this responsibility cannot be transferred to a machine.

Recently, Kincelova et al. investigated the use of BIM to improve fire protection integration in high-rise timber buildings (Kincelova et al., 2020), focusing on the integration of passive fire safety into the design process using BIM tools. A coherent method that addresses the issues of fire safety has been proposed. Moreover, to assess the possibilities of automated compliance checking, Kincelova et al. evaluates eight different checking tools in terms of code compliance checking applied to fire protection (Kincelova et al., 2019). Their results suggest that the existing code-checking solutions fail to address the fire protection challenges because it has specific needs in terms of modeling.

3.3.3 Literature review conclusion

Today, there is a growing need to use BIM for construction projects, in particular for mass timber projects. While some digital tools are already being used for the whole process, very few construction projects have used BIM-based model checking to verify digital models.

A review of the literature has shown that, in theory, BMC has great potential to accelerate the verification stage of a model. Indeed, when all the application's conditions are met, BIM offers impressive potential for productivity gains through digitalization. To date, this digital verification practice has been studied theoretically from certain points of view, but there is no general and systematic method dedicated to its implementation. Unsurprisingly, there is a gap between theoretical research and the practical use of such verification tools. There is also a lack of studies on verification needs according to different types of construction projects. For example, an infrastructure project will have different verification needs than a prefabricated modular construction. BMC allows the challenges of mass timber construction to be considered. Several conditions must be met before BMC can be implemented; we focus on how best to implement BMC and while considering the mass timber specificities.

3.4 Materials and Methods

3.4.1 Statement of purpose

This research work intends to facilitate the step of verification and compliance study of a digital model of a mass timber building. For this purpose, we first study the model-checking process in a general way, and then establish an overview of the possibilities offered by BIM-based verification, which is still missing from the literature. Considering the particularities of mass timber, we perform three model checking of mass timber model.

3.4.2 Objectives of the research

The main objective of the research is to propose a compliance study process based on BIM of mass timber digital models. For this, the specific objectives are:

- Characterize the business needs of mass timber projects
- Propose a general method, supported by tools, that synthesizes the steps of this process
- Establish the proof of concept of the advanced method through case studies

3.4.3 The main stages of the research

To conduct this research work, we followed distinct stages. First, understanding of the issues, developing a method and then validation of that method.

3.4.3.1 Evaluating the problem through interviews with experts in the field

The first step of the research process consists in understanding of the issues. The problem was evaluate through interviews with experts in the field.

Here, the issues are two-fold: the challenges concerning the adoption of mass timber construction in the AEC industry, and the adoption of model checking and the digitalization of the task. Our first researchs focused on off-site construction, DfMA, and related prefabrication issues, including the benefits and drawbacks of using BIM for prefabricated construction. While many company reports or guides on the subject of mass timber in the construction industry exist, few articles or scientific studies have studied it rigorously and scientifically, with only a small number of research papers having focused on BIM for mass timber projects. To understand how much mass timber construction is being used today, we investigated large mass timber structures that have been built recently. Most of these received a considerable amount of press, including these three: Brocks Common, a student residence in Vancouver; HoHo Vienna, an 84-meter-high building in Austria; and Mjøstårnet in Norway, which was the tallest CLT building in 2019 when it was built. We also consulted the Canadian standards, codes for construction, and norms about wood construction.

We had the opportunity to interview key players in the mass timber industry. We chose to interview the manufacturers and designers of a single recently built mass timber project. Focusing our case study on a single project allowed us to target some of the existing issues while conducting multi-perspective interviews. This is one of the limitations of our case study which is based on a single project, which does not represent a general case of mass timber projects. It would be interesting to extend the future work to other projects for a larger scale validation.

We conduct three interviews with following objectives: understand the challenges of mass timber, understand the issues and confirm the issues. We met with two engineers from a firm whose expertise is the manufacturing of CLT, and an architect who worked on the design of a CLT residential complex built in Montreal. We conducted a one-hour virtual interview with the engineers and then met with them in person for two hours. They discussed the problems in the collaboration between the architect, the MEP subcontractors, and the designer-suppliers of mass timber for a building project built in Montreal. In addition, they described the particularities of manufacturing at the factory, the relevance of using BIM for mass timber, and the difficulties linked to the non-standardization of this new material. Shortly after, we met virtually with the architect of the same project for a one-hour interview focused on the design difficulties to consider with mass timber and BIM.

3.4.3.2 Iterative development of the solution

We developed a checking method step by step in an iterative way. To build the steps, we performed simple verifications with several models. Those verifications allowed us to easily characterize the successive steps of the method, as well as to propose tools to help the user at each step. The process followed was an iterative one. The proposed tools are based on scientific theoretical foundations and summarize information about each scientific notion evoked.

3.4.3.3 Validation of the suggested method with material description

In the third step, we conducted three model-checking processes using the pro-posed method to make the proof of concept of the method. The three models are: a standard BIM educative model, the architectural model of Arbora a massive timber condominiums complex constructed in Montreal in the early 2010s, and the associated MEP model. Revit, its plugin Dynamo, Navisworks, and Solibri as were used to conduct tests and perform the checking case studies.

The three checking conducted were selected from various sources and types. These are all requirements related to the design of a mass timber building. The first consists in checking that the span of a CLT slab does not exceed 18 times its thickness. The second is to check the correct positioning of the drillings for MEP conduits. In the third, we verify that the same CLT panel appears a minimum of 20 times in the model. We then identify the recurring obstacles and the main difficulties in the process after conducting several model checking cycles.

3.5 Formalization and implementation of the suggested model-checking method

This section is dedicated to the presentation of the 5-step method to conduct BIM-based model checking (BMC). After a general overview, each step is detailed below.

3.5.1 General overview

The process of numerical model verification is complex. We study this process from A to Z and integrate it into a complete method for a non-expert user. To do this, we completely review and deconstruct each of the actions and steps necessary to perform model checking. Because the method is BIM-based, several factors come into play, in particular the digitalization of tasks.

This method is intended for both novice and intermediate designers who want to automate their processes. Even before performing model checking, with this method, a novice designer can better understand BMC's main challenges and gain an overview of the resources and application conditions required for performing model checking. The intermediate user who already performs digital model checking can learn more about the digitization of this task and its potential automation.

This method has a few conditions before it can be implemented. In particular, there must already be an exploitable 3D model of the building asset. Assuming that the virtual model is designed in the same way as the real building, checking the conformity of the model allows us to ensure the conformity of the real building. Thus, the method may not lead to a conclusive result if the model is not consistent and complete enough in its information.

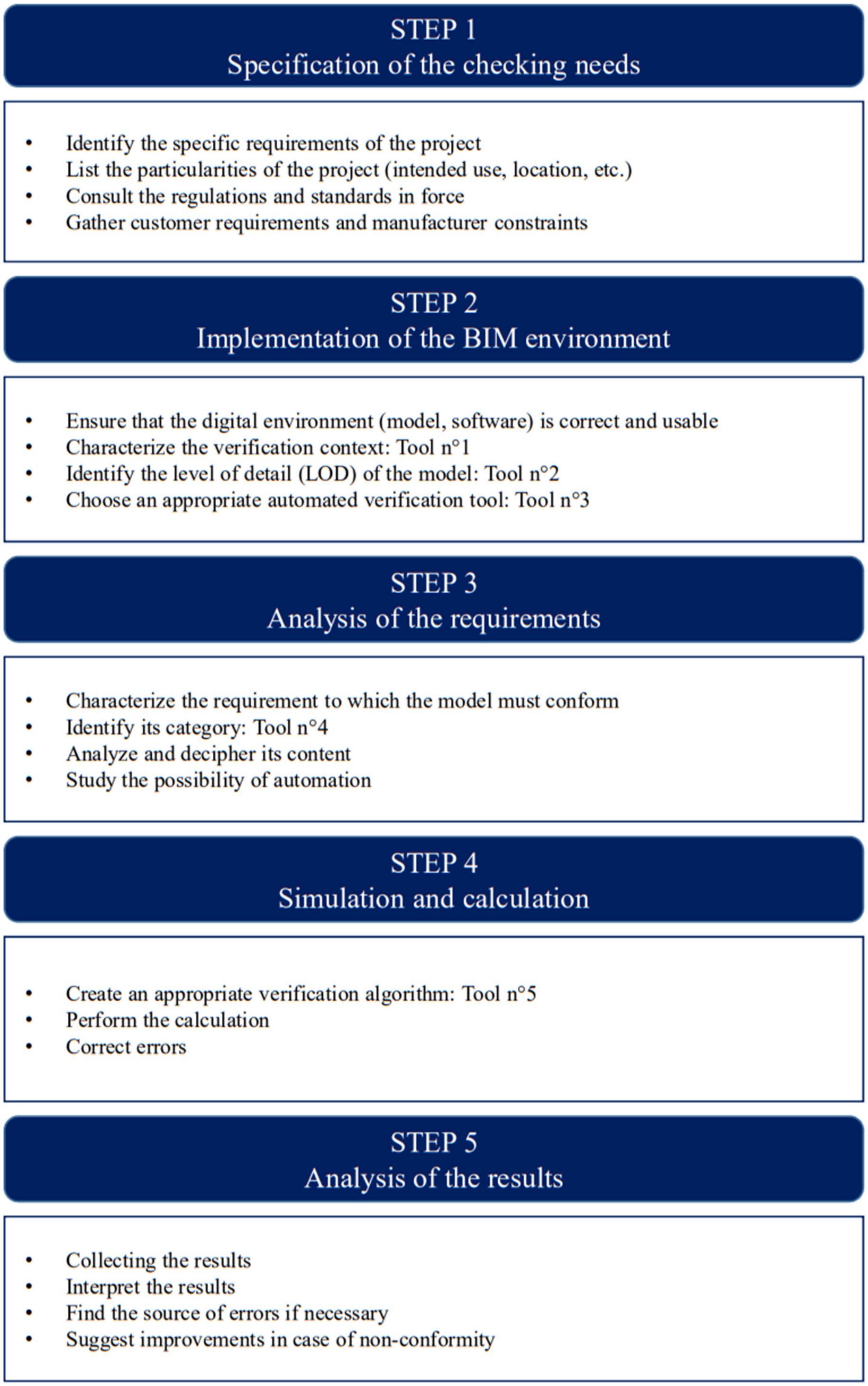
We identified five major steps of this checking process:

- STEP 1: Specification of the checking needs;
- STEP 2: Implementation of the BIM environment;

- STEP 3: Analysis of the requirements;
- STEP 4: Simulation and calculation of the results; and
- STEP 5: Analysis of the results.

Step one specifies what needs to be checked. Step two allows the user to adequately build the digital environment so that the modelis consistent and complete. Step three allows the user to decipher the content of the requirements to be verified in order to implement their verification. The simulation and the test calculations to study the conformity or the non-conformity of the model are performed in the fourth step. Finally, the last step is the analysis of the compliance results.

Figure 3.1 below presents an overview of the suggested checking method.



STEP 1
Specification of the checking needs

- Identify the specific requirements of the project
- List the particularities of the project (intended use, location, etc.)
- Consult the regulations and standards in force
- Gather customer requirements and manufacturer constraints

STEP 2
Implementation of the BIM environment

- Ensure that the digital environment (model, software) is correct and usable
- Characterize the verification context: Tool n°1
- Identify the level of detail (LOD) of the model: Tool n°2
- Choose an appropriate automated verification tool: Tool n°3

STEP 3
Analysis of the requirements

- Characterize the requirement to which the model must conform
- Identify its category: Tool n°4
- Analyze and decipher its content
- Study the possibility of automation

STEP 4
Simulation and calculation

- Create an appropriate verification algorithm: Tool n°5
- Perform the calculation
- Correct errors

STEP 5
Analysis of the results

- Collecting the results
- Interpret the results
- Find the source of errors if necessary
- Suggest improvements in case of non-conformity

Figure 3.1 Overview of the method

3.5.2 Step 1: Specification of the checking needs

The first step in the process concerns the project's requirements. The user has to identify the specific needs for checking for a project and at what stage of the project they have reached as different things need to be checked as the project progresses. Some projects, more than others, have particularities that will have an impact on verification: prefabricated buildings, building with high seismic constraints, mass timber buildings, building for certification, etc.

Characterizing the specifications of a project can be done by listing its particularities. This includes understanding a building's intended use, a description of the location of the construction site and the conditions of the building's use. It is also necessary to evaluate the progress of the project because some verifications are done at specific times. To identify the requirements to which the model must conform, it is necessary to consult the regulations in force, as well as to study the client's requirements and those of the builders. For example, for off-site construction, the builder may have certain constraints to verify.

3.5.3 Step 2: Implementation of the BIM environment

The second step in the method ensures that the BIM environment is well implemented. Depending on the maturity of BIM adoption in the company, implementing an adapted BIM environment may be relatively easy. The idea is to get a workable digital mockup of the project utilizing appropriate tools. Model compliance checking re-quires some specific BIM installation to take advantage of this digital technology. In BIM workflow, all design activities are model-driven (Nawari, 2018). The model is a central element of work, and so its quality is crucial. The model must contain the necessary information and properties to allow for automated compliance checking (Nawari, 2018).

To perform appropriate verifications, the company's digital BIM context, in particular the verification context, must be characterized (Suggested tool n°1). Next, the LOD (Level of development) of the model must be identified to ensure that the verifications can be done and that the model is consistent enough, which means that it contains the minimum required information (Suggested tool n°2). Once the model is usable, the appropriate software must be selected and the manner in which to conduct it (Suggested tool n°3). Also, it will be necessary to ensure that the format of the models is compatible with the software. Three suggested tools are detailed below.

3.5.3.1 Suggested tool n°1: Metamodel for checking context characterization

As observed in the related works, BIM-based model checking is an important and complex stage during the design of a built asset. It requires considerable resources that must interact with each other. The metamodel proposed in Figure 3.2 consists of a diagram with classes of elements and their properties. This allows to describe in detail a situation, i.e. the context of automated verification.

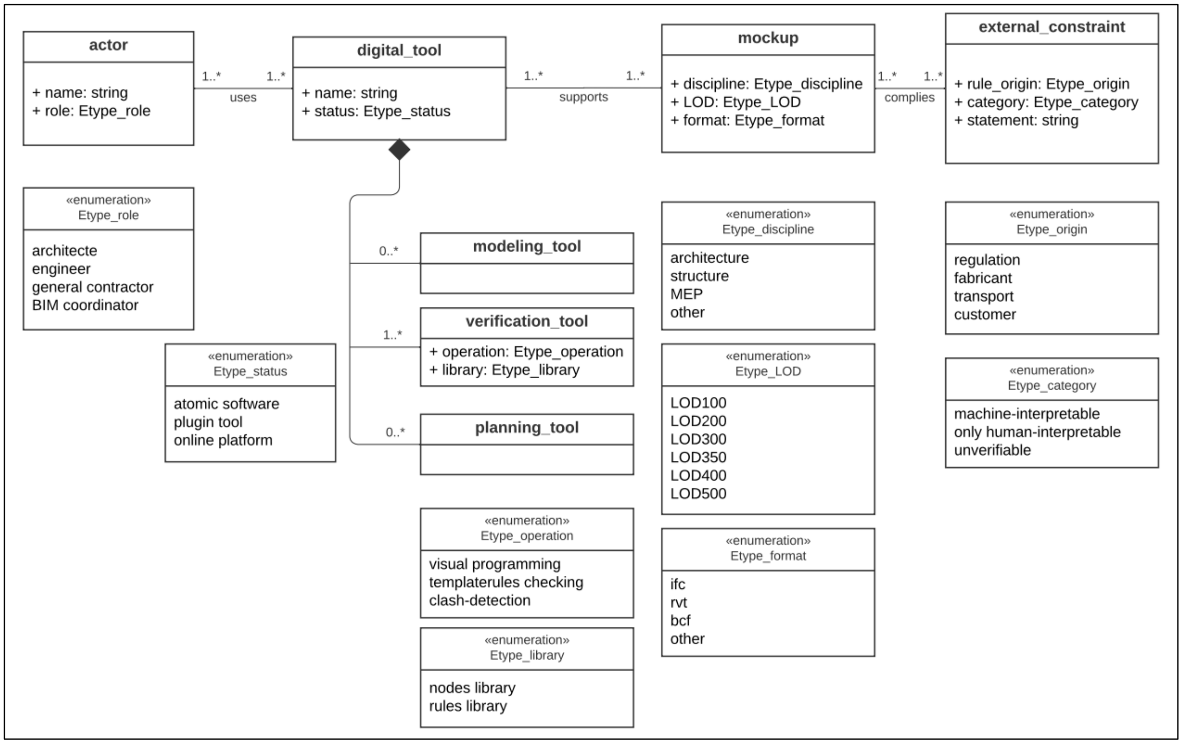


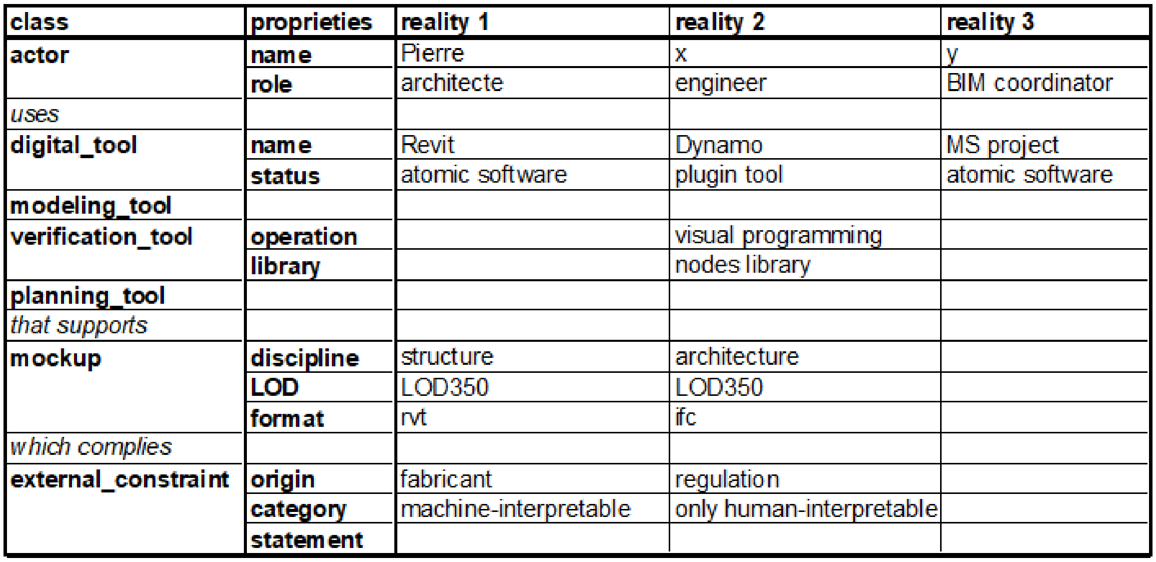
Figure 3.2 Metamodel of the required BIM environment

Model-driven engineering (MDE) approach suggests describing one reality with three modeling levels:

- M0: the reality;
- M1: the described reality;
- M2: the related metamodel.

For our study, level M0 is the architect's reality. For example: “Architect Pierre uses Revit, an independent modeling software, which supports a structural mock-up in format .rvt with a level of development LOD 350. The mockup has to be compliant with an external constraint required by the manufacturer, which is computer interpretable. Its statement is: “CLT slab length has to be less than or equal to 40 feet (12 m). “. Level M1 is described in Tableau 3.1.

Tableau 3.1 Level M1 of modeling



class	**proprieties**	**reality 1**	**reality 2**	**reality 3**
actor	**name**	Pierre	x	y
	role	architecte	engineer	BIM coordinator
uses				
digital_tool	**name**	Revit	Dynamo	MS project
	status	atomic software	plugin tool	atomic software
modeling_tool				
verification_tool	**operation**		visual programming	
	library		nodes library	
planning_tool				
that supports				
mockup	**discipline**	structure	architecture	
	LOD	LOD350	LOD350	
	format	rvt	ifc	
which complies				
external_constraint	**origin**	fabricant	regulation	
	category	machine-interpretable	only human-interpretable	
	statement			

3.5.3.2 Suggested tool n°2: Identification matrix of the LOD of a model

The LOD (Level of development) of an element indicates the level of detail of a digital element in the model. Knowing the exact LOD of a digital model the BIM deliverables to be specified and if the model is consistent enough to perform checking.

The LOD includes geometrical and non-geometrical information like quantities, the shape, size, location, orientation, interface(s) with other building systems, and fabrication-assembly-installation information (Bedrick, Ikerd, & Reinhardt, 2020). The LOD of elements may vary at different stages in the design and construction process. Each element in a model has its LOD. The LOD describes the information contained in the digital element, and so it determines the usability of the digital model. Starting from LOD300, the properties of an element can be measured directly from a model without referring to non-modeled information such as notes or dimension call-outs (Bedrick et al., 2020).

Based on the guide entitled The LOD Specification Part I from BIM Forum (Bedrick et al., 2020) and the basic LOD definitions developed by the AIA for the AIA G202-2013 Building Information Modeling Protocol Form, we suggest the items and values in Tableau 3.2, which summarizes the differences between each LOD. The first levels differ by the quality of the model element information: approximate, exact, or non-existent.

Tableau 3.2 Matrix for LOD identification

		LOD100	**LOD200**	**LOD300**	**LOD350**	**LOD400**	**LOD500**
System type	Symbol or generic representation	X					NOT USED
	Generic system		X				
	Specific system			X	X	X	
	Non-graphic information		X	X	X	X	
	Component existence	X	X	X	X	X	
The Model Element is graphically represented with	Quantity	*none*	*approximate*	*exact*	*exact*	*exact*	
	Shape	*none*	*approximate*	*exact*	*exact*	*exact*	
	Size	*none*	*approximate*	*exact*	*exact*	*exact*	
	Location	*none*	*approximate*	*exact*	*exact*	*exact*	
	Orientation	*none*	*approximate*	*exact*	*exact*	*exact*	
	Interfaces with other building system	*none*	*none*	*none*	*exact*	*exact*	
	Fabrication & assembly information	*none*	*none*	*none*	*none*	*exact*	
	Assest management	*none*	*none*	*none*	*none*	*none*	

Admittedly the concept of LOD is quite old and some find it a limited view of model development. To achieve better results, the level of required information must be defined for each single part of the model, according to real information needs.

3.5.3.3 Suggested tool n°3: Comparative analyses of four BIM-based checking tools

As observed in the related works, BIM-based model checking offers a wide range of checking possibilities depending on the tools used. We studied the checking capabilities of four BIM-based checking software packages. Our aim is to compare the four main commercially available digital verification tools: Dynamo, Grasshopper, Navisworks, and Solibri Model Checker (SMC). Each of them has been reviewed according to selected functionalities based on various criteria. The comparative study helps the model reviewer better understand the different software's capabilities.

Two comparisons were conducted: one comparing the user-tool interaction (see Tableau-A I-1) and the other focusing on the verification capabilities of the tools (see Tableau-A I-2). The comparison criteria are the functionalities expected by the verification software based on our software experience and on the literature. For the first comparative study, we regrouped the criteria into three categories: main features, interoperability, and usability. For the second comparison, the verification capabilities were compared, i.e., what can be checked and how these verifications are performed. In the tables below, the checked box means that the software has the feature in question. Blank boxes represent a lack.

The results suggest that these four software packages complement each other in every way. They all allow us to proceed with automated rule checking but in different manners. Among them, Navisworks seems to be the best software for reviewing the collision issues and to inspect the insides of mockup tanks to the walk-through option. Due to its large rule library, SMC is well suited for non-experimented users to check a global mockup in general. However, it may be limited because rule customization is relatively restricted with SMC. In contrast, both the visual programming tools – Dynamo and Grasshopper – offer a wide possibility of rule checking due to the customization in creating their own rules, but it takes considerable time to learn coding in visual programming. In terms of interoperability, even though they all have their specific native format, all four operate with the Industry Foundation Classes standard.

Even though Navisworks has multiple readable file formats, this tool has limited checking capabilities. SMC, with its rich database of ready-to-use rule templates, can perform much more checking and reviewing than Navisworks. Among these four tools, we conclude that Dynamo and Grasshopper, due to their visual programming functioning, offer the most flexibility in rules creation. Thus, the proposed approach contributes positively to highlighting the advantages of these verification tools.

3.5.4 Step 3: Analysis of the requirements

The third step in the method is to characterize the requirements with which the model has to be compliant. Requirements are expected specifications to fulfill a need. To identify their category, it’s interesting to know who expresses the requirement: it can be either a reference paper (codes, rules from regulations) or a need expressed ad hoc (manufacturer, customer).

To do this, the user has to first identify the category to which the requirement be-longs. In the literature, a few experts were interested in categorizing the different ways of doing model checking. We summarized those suggested classifications and categories of rule-checking in a table (Suggested tool n°4). Once the requirement category has been identified, the rule statement must be analyzed and deciphered. Depending on the rule category, we can study the possibility to automatize the checking. Then, the data and the calculation must be identified.

3.5.4.1 Suggested tool n°4: The various model-checking approaches

As described in the related literature, there are different levels of model-checking complexity and different types of model-checking approaches. Each type of checking can be classified in one of these categories. Focusing rather on the different checking approaches and multiple sources (Hjelseth, 2016), we synthesized them in Tableau 3.3 below.

Three checking categories can be distinguished: Validation Checking, Model Con-tent Checking, and Smart Environment Checking. Each checking category will be described.

Tableau 3.3 The three main checking categories

Checking categories	Description	Outcome nature	Specific checking actions
Validation Checking	Comparing the model with predefined criteria	Pass Fail	geometric & non-geometric rules verification clash detection hard clash management code compliance checking inquiry
Model Content Checking	Examining automatically the content of BIM model for a specific purpose (use of COBie)	Identified Not identified	missing information component check/content checking checking model data consistency deficiency detection modeling error/ systematic design error comparison of two models
Smart Environment Checking	Provides adapted solutions after analyzing the object's environment.	A modified model Adapted object Proposal Advice	spatio-temporal conflicts (workflow clash) windows & doors space arrangement clearance in front of / space checking soft clash management code compliance guidance best practice proposal for specific project (offsite, mass timber)

- Validation Checking: The first one is the Validation Checking type. It is the basic verification that consists in assessing if the model respects such precise parameters. This verification category is about compliance with rules: a model is compliant (pass) or is not compliant (fail); mainly to geometric rules or to code clauses. Such compliance studies return boolean output: this suggests that automation of the process is possible. Concerning code compliance checking, Malsane and Nawari have both studied the possible automation depending on the clause's statement nature (Malsane et al., 2015) and (Nawari, 2018). Both classifications are additional tools to sort rules or clauses to optimize the model-checking process and further lead to model-checking automation. Using Malsane's search, Validation checking may involve either declarative clauses (machine-interpretable clauses) or informative clauses (requires human interpretation) (Malsane et al., 2015). Automation is possible for declarative clauses and a couple of experts have worked on syntactic decoding to perform automation. Some identification criteria enable us to determine if a code clause is declarative or informative: for example, if there is a specific geometric test to perform if there are physical quantities to compare, etc. Frequently, when measurable physical quantities are at stake, it is about Validation Checking. The ideal context to proceed with Validation Checking is whether the user wants to check a structural mockup (mainly geometric constraint to check), to check compliance with a norm, a code, or a regulation, to study compliance with predefined criteria (if the client wants specific properties for example) and to automate a basic verification on a large amount of element. To implement it, some conditions are required. The model must contain all geometric information and the quantities indicated in the properties must be exploitable by the checking tool. An example of Validation Checking (declarative clause) can be: to check that all the walls have a minimum thickness of x mm.

- Model Content Checking: This verification is about verifying an element’s presence in a model. It consists in examining automatically the content of a BIM model for a specific purpose (use of COBie). The outcome is an identified or a non-identified object. The ideal context to proceed with Model Content Checking is whether the user wants to check an architectural mockup (architectural models are based on content: slab type 1, soils type 2, beams, concrete wall, etc.), to check the presence of some specific elements (for the maintenance phase for example) and to compare two models by their content. To implement it, some conditions are required. The user must ensure that the elements are filled in as objects in the model (for example, that a parallelepiped representing a wall is a wall object, and that sprinklers are sprinklers in the object name). An example of Model Content Checking can be: to check that the model conception is using those specific types of IPN beams with that dimensions.
- Smart Environment Checking: This verification consists in providing adapted solutions regarding an environment. The object itself observes its environment and automatically adapts to this by following embedded behavior rules or algorithms. It is a proposal that guides the designer to use a large range of most-used solutions according to best

practice rules. The outcome is a modified model with environment-adapted objects. The ideal context to proceed with Smart Environment Checking is whether the project is conducive to repeatable and predictable design (offsite construction). If the de-signer is inexperienced, this checking will guide him. To implement it, some conditions are required. Predefined rules and algorithms must be implemented, and a list of best practices has to be numerically established. It is a kind of AI process. An example of Smart Environment Checking can be: to return a whole building modeling based on a partial prefabricated modular design. Following parameters will be precisely defined: the site area dimensions, the number of floors, the unitary brick of modular elements, etc.

3.5.5 Step 4: Simulation and calculation

The fourth step in the methodology is to run the calculation; or simulation when automation is possible. The user has to create the appropriate checking algorithm ac-cording to the chosen checking tool. We illustrate the method in proposing a general Dynamo script entirely explained (Suggested tool n°5). Dynamo is one, among others, checking tool. The method works even using an other checking tool.

3.5.5.1 Suggested tool n°5: Example of a general Dynamo script

To conduct BIM-based model checking, we can use, among others, the tool Dy-namo. We observe a classical pattern to all verification start of Dynamo scripts. First, extract the required physical quantities (Elements of Categories) from the Revit ele-ments properties, then stock these data in lists. With the help of a Python script, ma-nipulate the extracted data and perform the calculation. Some nodes are dedicated to the visualization of the data which is very helpful for the user. Figure 3.3 is the common beginning Dynamo script used to perform checking.

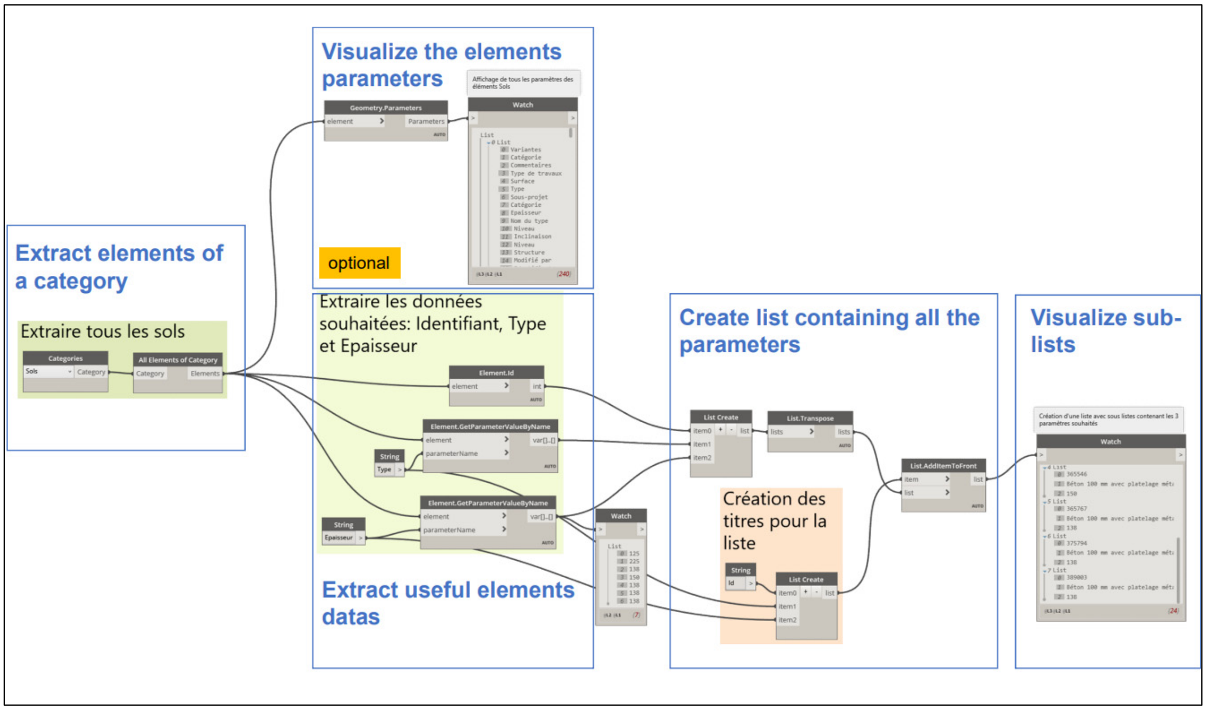


Figure 3.3 Classic beginning of a Dynamo script

3.5.6 Step 5: Analysis of the results

The fifth step in the methodology is to analyze the results and suggest improvements in case of non-compliance. It consists in collecting the results and interpreting them. In the end, the user wants to obtain a list of non-compliance in the model, for example in a list with the Id of all non-compliant elements of the mockup.

3.6 Proof-of-concept

This section describes the proof-of-concept of the developed method. Based on the literature and with the support of industrial partners, we use the context of mass timber offsite construction to proceed with the model checking. As noticed, this type of construction requires special checks. This case study studies three different scenarios of model checking. For each model scenario, we apply the suggested method step by step. We conclude this case study with a discussion of our results.

3.6.1 The context

For the context of this proof-of-concept, we considered the building code requirements and the requirements of two major industrial partners. We selected the specific context of the mass timber industry, an industry in full expansion today, as mass timber is a relatively recent and very promising technology. We focus on buildings structures constructed with CLT and glulam, both of which are prefabricated timber materials. They require specific manufacturing methods that make them entirely new building materials. Considering only constraints directly related to the design of the building, a mass timber model must comply with the following requirements from the current building codes:

- a CLT panel's dimensions should be adapted to the manufacturing capabilities of the plant;
- a CLT panel's dimensions should be adapted to the transport;
- a CLT panel's width should not be more than 2550 mm (according to CSA086)); and
- a CLT panel’s thickness is currently limited to 508 mm (20 in.) or less (Karacabeyli & Gagnon, 2019) (American National Standards Institute, 2018).

We consulted two industrial firms that work with such building materials. One is an engineering firm with recognized experience in designing and manufacturing mass timber products. They have their own wood processing plant. The second one is an architectural firm. Both firms design mass timber construction, including residential buildings and other structures (stations, bridges, etc.). In particular, they worked on the design and construction of Arbora: a residential mass timber building built in Montreal in 2018. Professionals from each firm described their main challenges encountered during that 2018 project.

This Arbora project is a recent example of mass timber residential construction. The complex is composed of three buildings (phases A, B, and C). Unlike the first two phases, only Arbora phase C was planned with BIM.

Experts from the two firms told us about the main issues encountered and those related to model compliance checking. Some difficulties concerning the connections were noted: contrary to light wooden frames, the connections for mass timber are not standardized. Each connection is unique and is designed by the mass timber manufacturer. This causes compatibility issues during construction, which could have been avoided during the design stage. A second problem comes from the nesting ─ the step of cutting the model into CLT panels. Instead of doing it manually, it could be auto-mated or at least optimized. The third problem involved the openings and the drilling. Designing and making the correct openings for MEP conduits in CLT panels required much back-and-forth between the two companies. For them, a verification tool that indicates in advance if a model is correctly designed in terms of MEP openings would be very useful.

Otherwise, a common structural requirement from the CLT manufacturer is to verify that the span of CLT slabs should not exceed 18 times their thickness, an important item to verify.

3.6.2 Case study

Our case study consists of three different aspects to checks. The first was to check that the span of the CLT slabs does not exceed 18 times its thickness (manufacturer's geometric constraint). The second was to check the correct positioning of the drillings for MEP conduits (constraint evoked by the industry). In the third, we verified that the same CLT panel appears a minimum of 20 times in the model (prefabrication constraint).

Three digital models were at our disposal: an educative BIM model, the architectural model of Arbora and the associated MEP model.

3.6.2.1 Checking example n°1: “The span of each CLT slabs should not exceed 18 times its thickness”

For this first example, we detail the method step-by-step. The objective here is to check that the span of each CLT slabs should not exceed 18 times its thickness.

Step 1: Specification of the checking needs

For the first step, the checking needs have to be clearly expressed, beginning with the specificity of the project. In this first application example, the project consists of a mass timber residential building construction. At this stage of the project, the design is in the development phase. Common geometrical uses of the design have to be made and the geometric compliance of the model has to be controlled. We identified the requirement to which the model must conform: it is a geometrical requirement whose exact rule statement is “The span of CLT slabs should not exceed 18 times their thick-ness”. The checking need is a geometric requirement.

Step 2: Implementation of the BIM environment

For the second step, the BIM environment has to be well implemented. First, we ensure that we have a workable digital mockup. The metamodel of the digital verifica-tion environment summarizes the following information:

Verification tool:
+name: Dynamo
+status: plugin tool
+operation: visual programming
+library: nodes library
mockup:
+discipline: architecture
+LOD: LOD300
+format: ifc
external_constraint:

+rule_origin: fabricant
+category: machine-interpretable
+statement: "The span of each CLT slabs should not exceed 18 times its thickness"

This is a requirement expressed by the fabricant. The LOD of the model has been identified thanks to the Tableau 3.2: exact quantity, shape, size, location, and orientation: LOD300. We choose Dynamo as a checking tool because it is well suited to verify geo-metrical requirements. As this tool's operation is controlled by visual programming, it is easy to extract specific information from the model for our purposes. Dynamo offers a wide flexibility in creating checking rules. In terms of interoperability, the model's file format and the tool are compatible.

Step 3: Analysis of the requirements

For the third step, the requirement has to be analyzed. First, we identify the re-quirement's category: it is a Validation Checking (because the model respects or does not respect a geometric rule statement). It is a declarative clause (Malsane et al., 2015), which means that the rule is computer-interpretable, and lastly, it corresponds to a conditional clause (Nawari, 2018). Analyzing the statement consists of identifying the physical quantities that have to be extracted, the comparison that has to be made, and the calculation that results from the statement. The statement's analysis shows that two dimensions have to be extracted and compared: that of the span and that of the thickness of the same CLT slab. The test calculation is thus: Is the span equal to or less than 18 times the slab's thickness? With this category of checking, automation is possible.

Step 4: Simulation and calculation

The simulation and the calculations are made in the fourth step. Considering that Dynamo has been chosen, we create an appropriate checking algorithm: a script that enables to link between the model and the calculation. This geometrical verification consists of extracting different geometrical quantities from the model (length of the frames and thickness of the floors) and then performing the test calculation. The Dynamo tool allows a verification script to be created easily, with the following steps:

1. extract the slab thicknesses;
2. create a thicknesses list;
3. extract the span lengths;
4. create a span list;
5. create python code that checks the condition for each identical level from the information in both lists; and
6. return a list of non-compliances with the identifiers of the non-conforming frames and floors and their information (Level, Floor Id, Thickness, Span Id).

Figure 3.4 below shows the script used in verification n°1.

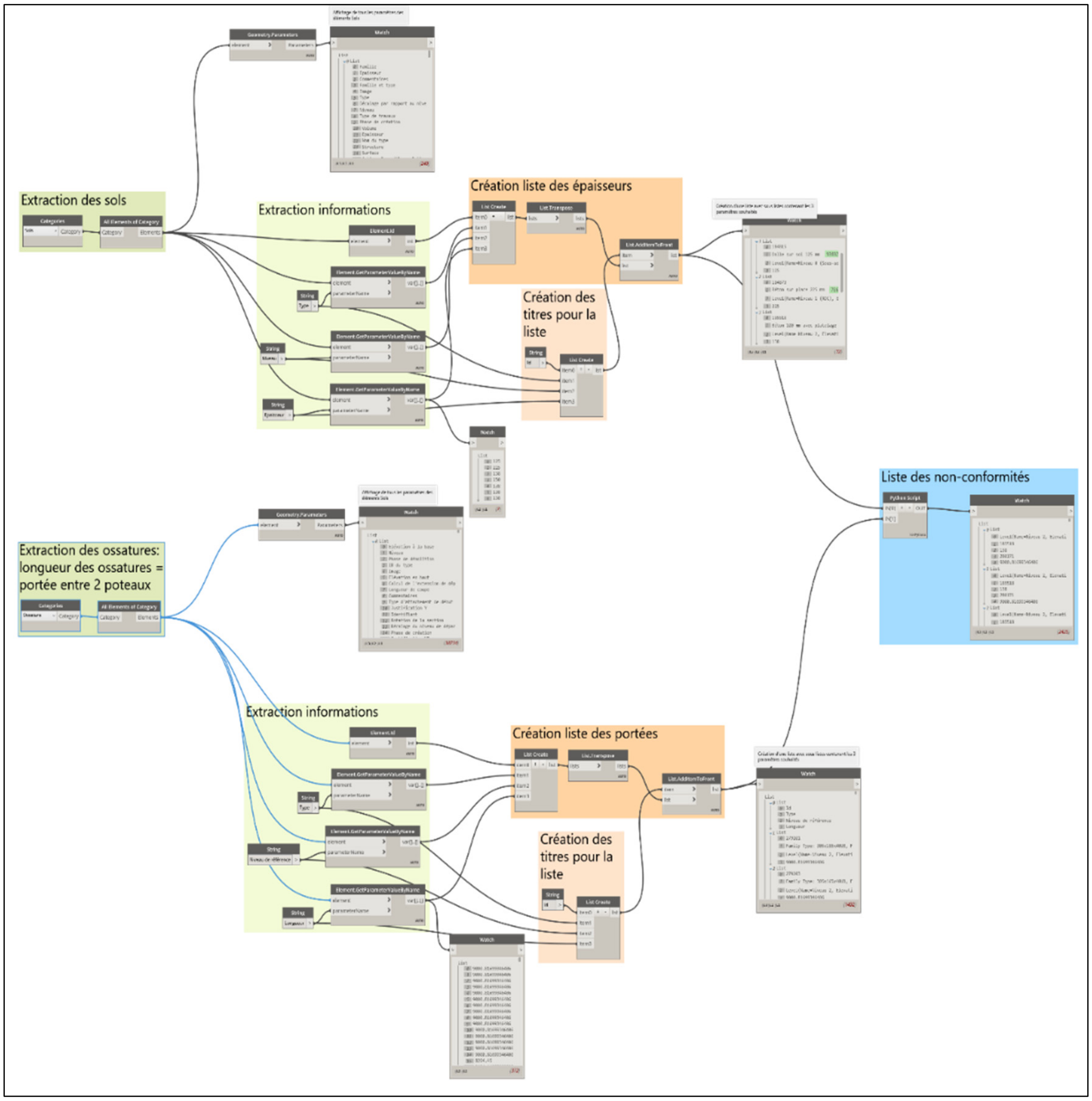
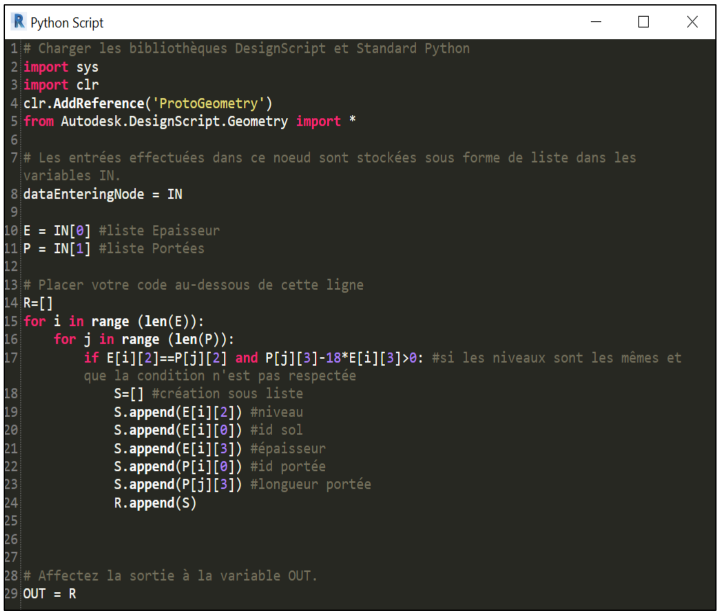


Figure 3.4 The Dynamo script for verification n°1

Dynamo allows the insertion of a Python code in the script. The code used allows ─ with different lists ─ to extract and return the non-conformance information in a final list, as presented in Figure 3.5.



```python
# Charger les bibliothèques DesignScript et Standard Python
import sys
import clr
clr.AddReference('ProtoGeometry')
from Autodesk.DesignScript.Geometry import *

# Les entrées effectuées dans ce noeud sont stockées sous forme de liste dans les variables IN.
dataEnteringNode = IN

E = IN[0] #liste Epaisseur
P = IN[1] #liste Portées

# Placer votre code au-dessous de cette ligne
R=[]
for i in range (len(E)):
    for j in range (len(P)):
        if E[i][2]==P[j][2] and P[j][3]-18*E[i][3]>0: #si les niveaux sont les mêmes et que la condition n'est pas respectée
            S=[] #création sous liste
            S.append(E[i][2]) #niveau
            S.append(E[i][0]) #id sol
            S.append(E[i][3]) #épaisseur
            S.append(P[i][0]) #id portée
            S.append(P[j][3]) #longueur portée
            R.append(S)



# Affectez la sortie à la variable OUT.
OUT = R
```

Figure 3.5 Python code for verification n°1

<u>Step 5: Analysis of the results</u>

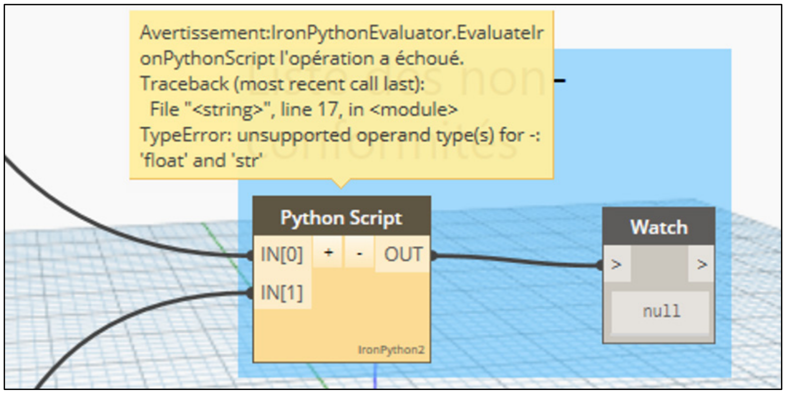
The results are analyzed in the fifth step. Several difficulties were found with the Ar-bora model: an error message was systematically returned (see Figure 3.6), an error a type not supported in the Python code. The information from the properties of the elements (Soils, Frames) were not interpretable by the calculation. Type problem with P[j][3] and E[i][3] indicated that IronPython.Runtime.Types.Python was not recognized as a number with which to perform a calculation. On the contrary, the Dynamo script worked correctly with the BIM educative model; we only had to fill in some missing floor thicknesses at the beginning. At the end, this first checking was completed and we conclude that there are some slabs that do not comply with the requirement studied.

For this checking n°1, the difficulties encountered were:

- Arbora model: A type of information was not readable by the Dynamo script (Type: IronPython.Runtime.Types.Python)

- BIM educative model: A mock-up with missing, inaccessible, or non-indexed information (thickness of the floor)

These obstacles to verification only concerned the digital model and its properties.



```
Avertissement:IronPythonEvaluator.EvaluateIr
onPythonScript l'opération a échoué.
Traceback (most recent call last):
  File "<string>", line 17, in <module>
TypeError: unsupported operand type(s) for -:
'float' and 'str'
```

Figure 3.6 Unsupported type error

3.6.2.2 Checking example n°2: “Drillings for MEP conduits must be correctly positioned”

For this second application example, we again describe how we proceed step-by-step according to the developed method. This example aims to check the drillings and their correct positioning.

<u>Step 1: Specification of the checking needs</u>

In this second application example, the project consists of a mass timber residential building construction. At this stage of the project, the design is at the end of the development phase, and so the focus is on more precise details. We identified the requirement to which the model must conform: a geometrical requirement whose exact rule statement is “Drillings and openings for MEP conduits must be correctly positioned.” The checking need is a positioning and geometric requirement.

<u>Step 2: Implementation of the BIM environment</u>

For the second step, the BIM environment has to be well implemented. First, we ensure that we have a workable digital mockup: the architectural model of Arbora. The metamodel started to be used but soon a major problem was noticed: the architectural model does not present any drillings for connection or openings for MEP conduits. If something is not modeled digitally, it is impossible to proceed with any kind of verification about the digital element. As the required information is not modeled, this verification cannot be completed.

For this checking n°2, the difficulties encountered were:

- Arbora model: Openings are not modeled

3.6.2.3 Checking example n°3: "The same CLT panel must appear a minimum of 20 times in the model"

As with the other two, we detail how we implement the developed method for this application example. The objective here is to check that the same type of CLT panels is present a minimum of 20 times in the model.

Step 1: Specification of the checking needs

In this third application example, the project consists of a mass timber residential building construction. At this stage of the project, the design is in the development phase, and so basic rules about the geometry and the elements' presence must be followed. We identified the requirement to which the model must conform: a basic rule concerning the presence of elements whose exact rule statement is "The same CLT panel must appear a minimum of 20 times in the model." The checking need consists of counting the number of occurrences of an element in the whole model.

Step 2: Implementation of the BIM environment

For the second step, the BIM environment has to be well implemented. First, we ensure that we have a workable digital mockup: the architectural model of Arbora. The metamodel of the digital verification environment summarizes the following information:

Verification tool:
+name: Dynamo
+status: plugin tool
+operation: visual programming
+library: nodes library
mockup:
+discipline: architecture
+LOD: LOD300
+format: ifc
external_constraint:
+rule_origin: other
+category: machine-interpretable
+statement: The same CLT panel must appear a minimum of 20 times in the model."

This is a requirement expressed by the fabricant. The LOD of the model, LOD300, has been identified thanks to Tableau 3.2. We choose Dynamo as a checking tool because it is well suited to verify quantity requirements, and it offers a wide flexibility due to visual programming. In terms of interoperability, we verified that the model file format and the tool are compatible.

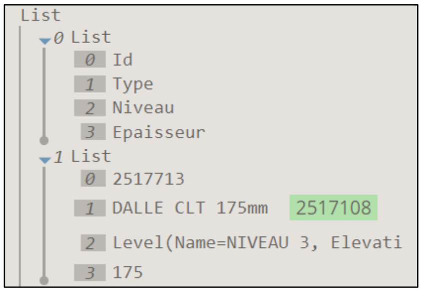
Step 3: Analysis of the requirements

For the third step, the requirements have to be analyzed. First, we identify the requirement's category: it belongs to Model Content Checking. The statement's analy-sis shows that each element with type "DALLE CLT 175mm" must be extracted and then counted. The test calculation is thus: Is the same CLT panel model present at least 20 times in the model? With this category of checking, automation is possible.

Step 4: Simulation and calculation

The simulation and the calculations are made in the fourth step. Considering that Dynamo has been chosen, we create an appropriate checking algorithm: a script that can create a link between the model and the calculation. We focus on the CLT slab with type number 2517108 and 175 mm thickness. Its type is: “DALLE CLT 175mm”, as shown in Figure 3.7.

1. extract the soils
2. create a list of Id and Type of soils
3. python code that filters all the soils by type
4. return a list of all soils of the desired type DALLE CLT 175mm (→length of list)



```
List
 0 List
   0 Id
   1 Type
   2 Niveau
   3 Epaisseur
 1 List
   0 2517713
   1 DALLE CLT 175mm   2517108
   2 Level(Name=NIVEAU 3, Elevati
   3 175
```

Figure 3.7 CLT slab to extract

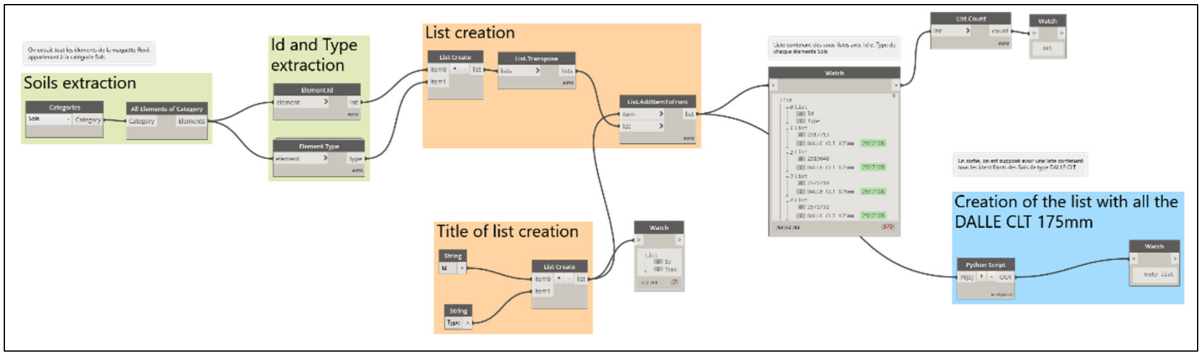
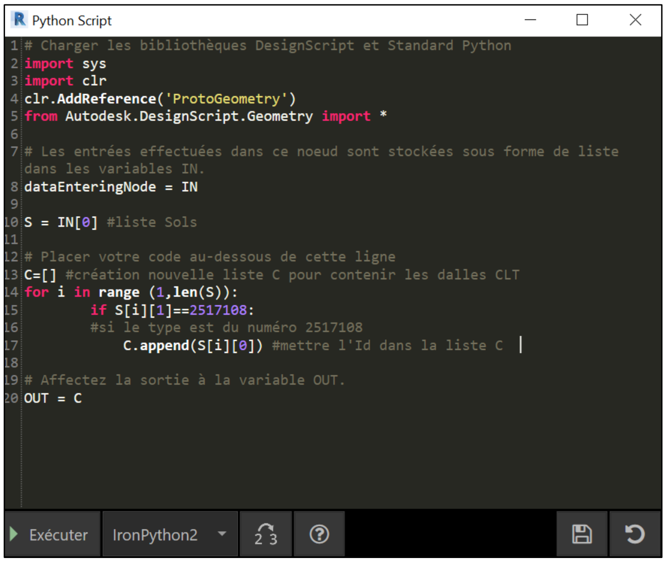


Figure 3.8 Dynamo script for verification n°3

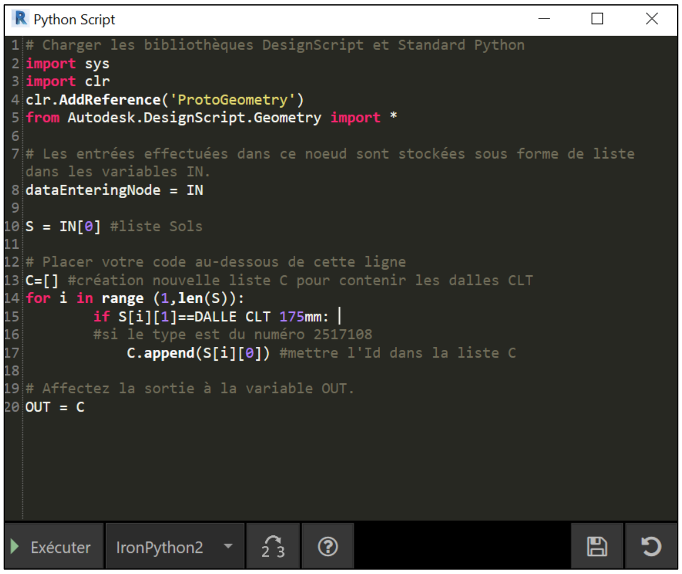
We create a Dynamo visual programming script (see Figure 3.8). The first step is the extraction of all soils. From that category, we extract their Id and Type specified in the properties, and put all the data into lists. Next, a Python script has to be written: it filters all the soils by type. The output lists all the soils with the following type: DALLE CLT 175mm 2517108. The length of the list thus directly indicates the number of CLT slabs.

But, the scripts returned an empty list. One difficulty is to identify the interpretable name of S[i][1]. Many tests with other parameters were conducted, and proved that the Python scripts are correct. The issue seems to come from the name of the Type. The Type entered in the soil's properties is "DALLE CLT 175mm" with an identifier 2517108. This name does not appear to be interpretable as a type by the program. Neither the name "DALLE CLT 175mm" nor the identifier 2517108 is interpretable by the code (see Figure 3.9 and Figure 3.10). This has been identified as is a problem about the information type. Even though it is a number, it is not a number that the machine can interpret.



```
# Charger les bibliothèques DesignScript et Standard Python
import sys
import clr
clr.AddReference('ProtoGeometry')
from Autodesk.DesignScript.Geometry import *

# Les entrées effectuées dans ce noeud sont stockées sous forme de liste dans les variables IN.
dataEnteringNode = IN

S = IN[0] #liste Sols

# Placer votre code au-dessous de cette ligne
C=[] #création nouvelle liste C pour contenir les dalles CLT
for i in range (1,len(S)):
        if S[i][1]==2517108:
        #si le type est du numéro 2517108
            C.append(S[i][0]) #mettre l'Id dans la liste C

# Affectez la sortie à la variable OUT.
OUT = C
```

Figure 3.9 Python code for verification n°3



```python
# Charger les bibliothèques DesignScript et Standard Python
import sys
import clr
clr.AddReference('ProtoGeometry')
from Autodesk.DesignScript.Geometry import *

# Les entrées effectuées dans ce noeud sont stockées sous forme de liste dans les variables IN.
dataEnteringNode = IN

S = IN[0] #liste Sols

# Placer votre code au-dessous de cette ligne
C=[] #création nouvelle liste C pour contenir les dalles CLT
for i in range (1,len(S)):
        if S[i][1]==DALLE CLT 175mm: 
        #si le type est du numéro 2517108
            C.append(S[i][0]) #mettre l'Id dans la liste C

# Affectez la sortie à la variable OUT.
OUT = C
```

Figure 3.10 Second python code for verification n°3

For this checking n°3, the difficulties encountered were:

- Arbora model: Unidentifiable soil type

3.7 Discussion and conclusion

The study aims to offer AEC professionals a method that syntheses the stages of the model-checking process. Ideally, we want the user to be able to use this method to assess whether a design complies with the manufacturing capability, as a requirement among others, at the mass timber plant. This work aims to make model checking accessible to everyone, and to show the possibilities and obstacles related to this task.

While most studies have focused on automated rule checking and code compliance checking, we cover a broad set of model checking based on the use of BIM technology. Our approach brings new elements into the field: we have detailed the requirements needed to proceed with model-checking, and we contributed generally to the democratization of the use of mass timber as a construction material, as verified in case study. The method synthesizes the options and possibilities offered by the BIM verification of the models, characterizes the conditions to automate the task, and facilitates the user in the implementation of the digital environment. It allows users, whether they are beginners or advanced, to anticipate and more easily anticipate the process of BIM-based model checking.

We compared the performance of different verification software, explored the conditions of application of the different types of verification, and provided concrete tools to carry out these verifications at each step. Through our applications, we proved that the tools are powerful and allow us to perform verifications based on the BIM approach. In addition, this work has brought something new to the field of mass timber construction by analyzing the design issues related to this material during the design stage and the model checking stage. We used Dynamo primarily for our verification. Due to its visual programming mode of operation, thus its great flexibility to create checking rules, we found it to be the most suitable tool for performing our verifications. However, some difficulties appeared.

Indeed, some problems appeared when we attempted to apply the method in the case studies. We had a problem with an impossible interpretation of the data, which meant that our checks could not be completed. For the application cases, it was expected that the three simple checks could be conducted completely, and we thought that the data would be more easily usable. We did not expect to have to deal with data issues that could not be interpreted by the verification software. We were surprised by the recurrent problems of incorrectly filled in or missing information in the model. Both of these issues showed how BIM requires first and foremost having a great digital mockup. It has to contain all the necessary information, and the information must be usable and interpretable by the checking software. Many times, the nature of the in-formation in the model was not in the format required by the software. It was not possible to complete the verification because the calculation via the software could not be done. However, the three case studies demonstrated that the five-steps method lead to a conclusive model checking process. In fact, we achieve to apply the whole method using the suggested tools, and it was possible to understand why some case studies were not successful.

Our research has a few limitations. First, our interviews and case studies focused on a single mass timber project, which is not representative. Also we had only one mass timber model at our disposal, which limited the diversification of the case studies and the comparison. Nevertheless, our contribution to the research consisted in pro-posing a general method to study model conformity according to requirements.

We note from this research that the software packages dedicated to model check-ing are numerous and promising. They allow for many possibilities, and have a great potential to make the model checking step worthwhile. However, having powerful software without usable models is useless. To fully benefit from these tools, the digital mockups have to be very well modeled and their data rigorously updated and verified. While our work has been confronted with many obstacles, we see this research on BIM-based model checking as an exploration of this use of BIM to perform model checking. In total, we have addressed several aspects of model checking (synthesis of possible verifications, automation of certain verifications, comparison of verification software, etc.). BIM verification tools have been shown to help verify multiple requirements models, not just those from building codes. For example, the requirements related to the manufacturing capacity of a plant can be tested. Some other requirements from other checking categories can also be considered. For the category model content checking, we can verify if there are glulam beams with x-y sections in the model. For the category smart environment checking, a model which fits and adapts itself in suggesting a mass timber building with a unique model of CLT panel and a unique model of glulam beam could be an interesting aspect.

For future work, it would be interesting to study in detail the verification of pre-fabricated 3D modular models. Concerning mass timber in particular, it would also be interesting to study the design and verification issues encountered on other mass timber projects for example.

This work will allow us to make recommendations to the industry. It is very important to specify the intended uses of digital models in the BIM plan. The project should be planned around the model and therefore designed accordingly so that it can be able to operate it.

CHAPITRE 4

DISCUSSION DES RÉSULTATS

4.1 Synthèse des vérifications menées

Lors de l'étude de cas, nous avons effectué trois vérifications différentes par leur nature, leur provenance et leur complexité. La première vérification consistait à contrôler que la portée des dalles de CLT n'excède pas 18 fois son épaisseur. La deuxième consistait à vérifier que percements pour conduits MEP étaient correctement positionnés. La troisième consistait à vérifier qu'un même panneau de CLT apparaisse un minimum de 20 fois dans le modèle. Nous nous attendions à pouvoir facilement effectuer ces calculs de vérifications avec les logiciels BIM, mais cela n'a pas été le cas à chaque fois. Pour chacune des vérifications, nous avons été confrontés à quelques difficultés.

Dans la vérification n°1, on a d'abord construit et testé le script Dynamo sur un modèle 3D BIM à usage éducatif, donc pas en bois massif. L'épaisseur de certains sols n'était pas renseignée comme paramètre Épaisseur, il a fallu les renseigner à la main dans les paramètres du modèle. L'épaisseur était uniquement écrite dans le titre de l'élément de la catégorie Sols. Une fois qu'on a renseigné cette information manquante, le script créé fonctionne sans souci pour ce modèle. Puis, en lançant le même script Dynamo sur la maquette architecturale de bois massif, on a été confronté à une erreur de lecture de données. Un message d'erreur était retourné systématiquement : il indiquait que l'opération de calcul a échoué à cause d'une erreur de type. Le type de la longueur de la dalle (la portée) et celui de l'épaisseur de la dalle ne semblent pas être supporté pour effectuer le calcul. Malgré qu'un chiffre soit renseigné comme propriété, il semble ne pas être considéré comme un nombre avec lequel on puisse effectuer un calcul pour l'ordinateur. Nous n'avons pas réussi à surmonter cet obstacle. Ces deux obstacles sont à propos d'un mauvais renseignement des grandeurs en propriété. Pour la première étude de cas, nous avons prouvé que le script de vérification Dynamo fonctionnait, bien que seulement sur la maquette BIM éducative.

Dans la vérification n°2, on a souhaité comparer les ouvertures du modèle architectural avec l'emplacement des conduits MEP du modèle MEP. On a été très rapidement confronté à une difficulté majeure : les ouvertures pour conduits MEP ne sont pas modélisées. Il nous a été impossible de continuer cette vérification. Cet obstacle est à propos d'une non-modélisation. Pour la deuxième étude de cas, la vérification menée n'a pas pu aboutir.

Dans la vérification n°3, on a souhaité compter de nombre d'occurrence d'une même dalle de CLT dans le modèle bois massif. Ici aussi, on a été confronté à un souci d'interprétation d'une information en propriété. Il nous a été impossible d'extraire par type tous les sols avec le type "DALLE CLT 175mm". Pourtant renseigné par "DALLE CLT 175mm" avec le numéro d'identification 2517108, le code python n'a pas permis de sélectionner les dalles de CLT en question. Nous n'avons pas réussi à surmonter cet obstacle. Cet obstacle est à propos d'une impossible identification d'un type d'un élément sols. Pour la troisième étude de cas, la vérification menée n'a pas pu aboutir.

Voici le récapitulatif des difficultés rencontrées:

- vérification n°1 : information d'épaisseur de sols manquante;
- vérification n°1 : type d'une grandeur en propriété non interprétable comme un nombre par python pour effectuer un calcul;
- vérification n°2 : non-modélisation d'éléments intervenants dans la modification;
- vérification n°3 : identification impossible par python d'un type de sols.

Nous avons réussi à les surmonter dans le cas de la vérification n°1 où l'information d'épaisseur de sols était manquante en la renseignant à la main. Toutes ces difficultés sont liées au modèle numérique, plus précisément aux éléments (non-modélisés), aux propriétés des éléments (mal-renseignées, non-renseignées) et à leur type dans le modèle Revit qui n'est pas interprétable par le code python pour effectuer des calculs.

4.2 Mise en perspective du travail de recherche

Bien que plusieurs difficultés aient été rencontrées, il est important de mettre en perspective le travail de recherche. Il s'inscrit dans un contexte de recherche universitaire au niveau de la maîtrise. Les ressources utilisées ont été celles à disposition, elles sont donc limitées et nous avons dû nous en contenter. Notamment, nous n'avons réussi à obtenir qu'une seule maquette numérique d'un bâtiment en bois massif. Nous nous sommes rendu compte lors des tests de vérifications que cette maquette ne présentait pas toutes les caractéristiques souhaitées. Concernant les logiciels utilisés, aucun manque particulier ayant été un obstacle pour notre recherche à déplorer. Nous avons donc appliqué les outils BIM dont nous disposions à la maquette bois massif ainsi qu'à un autre modèle 3D conventionnel à destinée éducative.

Il est aussi important de préciser que la problématique de recherche du mémoire ne provient pas de l'industrie. Il s'agit d'un sujet proposé par la Chaire industrielle de recherche sur la construction écoresponsable en bois (CIRCERB) de l'Université Laval au Département des sciences du bois et de la forêt. De ce fait, nous avons dû obtenir moi-même les maquettes et procéder avec les ressources à disposition. Dans un contexte différent où le sujet aurait été exprimé par les besoins de l'industrie, un modèle numérique plus précis aurait probablement été fourni. Aussi, la recherche aurait pu être plus intéressante si nous avions disposé d'un deuxième modèle numérique en bois massif plus fournie.

Au vu de notre contexte de recherche, nous avons malgré tout réussi à mener quelques vérifications de modèle et à expliquer l'origine des problèmes rencontrées. Cela tient lieu de preuve de concept de la méthode innovante suggérée. La méthode est innovante en ce sens qu’elle apporte une synthèse générale mettant en lumière les enjeux de la vérification de modèle basée sur le BIM.

4.3 Contribution à la recherche

Ce travail de recherche a apporté sa pierre à l’édifice aux domaines suivants : la vérification de modèle basée sur le BIM et les constructions en bois massif. Cette contribution a permis d’apporter une méthode étape par étape pour mener à bien une vérification de modèle basée sur le BIM. Nous avons apporté du nouveau à travers la métamodélisation de l’environnement digital BIM requis, la matrice d’identification du LOD d’un modèle, les deux analyses comparatives des performances de quatre logiciels de vérifications BIM, la synthèse des catégories de vérifications de modèle et l’exemple d’un script de vérification Dynamo.

4.4 Travaux futurs

Ce travail de recherche avait pour but premier de favoriser le choix du bois massif comme matériau durable pour de nouvelles constructions au Québec. Puis est venue l’idée d’évaluer ─ grâce au BIM ─ si un modèle de bâtiment bois massif est conçu conformément aux capacités manufacturières de l’usine de production de CLT. Cela devait tenir compte de la caractéristique du bois massif, à savoir la préfabrication hors-site, et montrer que le BIM est justement adapté pour ce type de projet. Cet objectif est rempli car la recherche a étudié les caractéristiques du bois massif et leurs conséquences directes sur la conception du bâtiment. On a montré en quoi la vérification de modèle était différente pour le bois massif. Aussi, on a démontré en quoi le BIM est très pertinent pour mener à bien des projets de bois massif.

Dans de futurs travaux de recherche, il serait intéressant de prolonger l’étude sur le BIM au service des projets bois massif. Concrètement, étudier comment le BIM, notamment le BIM 4D, permet de prévoir la logistique du chantier : expédition de l’usine de préfabrication, gestion de l’approvisionnement des modules sur chantier, stockage et entreposage sur chantier, assemblage. Aussi il serait intéressant de travailler sur les possibilités de standardisation des dimensions des CLT et lamellé-collé.

CONCLUSION

En phase de conception, le BIM présente aujourd'hui un potentiel majeur au domaine d'étude de conformité des modèles numériques. Mais de nombreux enjeux persistent pour étendre l'utilisation de la vérification de modèle basée sur le BIM en pratique. Ce travail de recherche a donc consisté à établir une méthode générale de vérification basée sur le BIM faisant la synthèse des étapes et des challenges associés. La méthode de cinq étapes proposée a été construite par processus itératif en manipulant modèles et logiciels de vérifications. Elle est supportée par cinq outils qui aident l'utilisateur dans l'application de la méthode. Ils synthétisent l'information essentielle à la mise en place des outils digitaux relatifs au BIM. L'étude de cas sur maquettes numériques en bois massif a été faite selon deux objectifs : un, effectuer la preuve de concept de la méthode avancée, et deux, montrer que le BIM fortement aide à la vérification des conceptions en bois massif.

D'autre part, les enjeux rencontrés lors de l'étude de cas ont mis en évidence la problématique liée à la qualité du modèle. En effet, nous avons pu voir que l'automatisation de la vérification nécessite des modèles numériques d'excellente qualité. Ils doivent être créés de façon très précise et les informations doivent toutes être renseignées. Cette problématique est intrinsèque à tous les domaines du BIM qui souhaitent manipuler les données contenues dans le modèle. Il s'agit d'un des enjeux majeurs.

Ce travail de recherche nous permet de retenir que les modèles numériques de bâtiment doivent être extrêmement précis et contenir toutes les infos pour pouvoir les exploiter, que le BIM permet assurément de faciliter la vérification de conformité d'un modèle, notamment la conformité vis-à-vis de la capacité manufacturière à l'usine de production pour les constructions hors-site. Nous avons démontré que le BIM est intéressant pour gérer les projets de bois massif.

Ainsi, le travail de recherche a posé un cadre général dans le contexte de la vérification de modèle basée sur le BIM et a démontré la nécessité de poursuivre le développement de ce domaine prometteur.

ANNEXE I

COMPARATIVE ANALYSES OF FOUR BIM-BASED COMPLIANCE CHECKING TOOLS

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Abstract. In much of the world, digital tools are already being used in industry for the everyday process of work, leading to better productivity and quality. But, according to recent studies, the architecture engineering & construction industry is lagging behind in this move to digital processes. Very few construction operations have been automated, and productivity in the construction industry is still low in 2022. However, several digital approaches and tools have been developed for the construction industry in the last few decades. Among them, the Building Information Modeling (BIM) approach has the potential to significantly improve processes in the construction industry. BIM uses a multi-dimensional digital mockup to document and simulate the design, construction and operation of a built asset. Automatic code compliance checking is one of the many proposed BIM uses. It is defined as "a process in which code validation software is used to check the model parameters against project-specific codes". While several software systems have been proposed, the existing tools are not yet commonly used and it is still difficult for end users to select the one most suited to their needs. As observed, there is a lack of studies comparing and assessing the verification tools available in today's software market. We aim to compare the four main commercially available digital verification tools. Two comparisons were conducted. In the first one, each tool was reviewed according to some desired functionalities based on criteria summarized in three categories:

features, interoperability and usability. In the second one, we studied the whole rule-checking process in detail. The results suggest that Navisworks offers interesting functionalities for reviewing collision issues and to inspect the inner view of a mockup (walk-through). Due to its large rule library, Solibri Model Checker is well suited to assess a global mockup; nevertheless, it may be limited because its rule customization is restricted. On the contrary, both visual programming tools – Dynamo and Grasshopper – offer a broad possibility for rule checking due to the customization available to create their own rules, but there is a long learning code to master coding in visual programming.

Keywords: Building Information Modeling, Code compliance checking, Comparative analysis, Rule checking, Digital mockup.

1 Introduction

The adoption of digital technologies for construction projects is still slow: this partly explains the low productivity of the construction sector. Indeed, global labor-productivity in construction has grown only 1 percent a year over the past two decades, compared with growth of 2.8 percent for the total world economy and 3.6 percent in manufacturing (Barbosa, Mischke, & Parsons, 2017). But according to McKinsey & Company, the sector's productivity could increase by up to 60 percent in integrating digital technology, new materials and advanced automation in particular (Barbosa et al., 2017).

For several years, a tremendous amount of Building Information Modelling software systems have been available on the market in several categories of tools: computer-aided design (CAD), 3D model visualization, BIM management, BIM coordination and model checking. Companies who want to adopt the BIM approach must select their tools and software according to their needs and resources (employee expertise, financial budget, material, IT equipment, etc.).

Design coordination and conflict detection are some of the most common and highly valued uses of Building Information Modeling (BIM) (Zadeh et al., 2018). BIM also promises to support automatic verification of building design (Li, Martins, & Ireman, s.d.), rather than the manual, iterative and time-consuming evaluation of CAD drawings. Automatic code compliance checking is defined by Messner et al. as "a process in which code validation software is used to check the model parameters against project-specific codes" (Messner et al., 2019). Several software systems have been proposed, but the existing tools are not yet well utilized, and it is still difficult for end users to select the system most suited to their specific needs. As observed in the literature, there is a lack of studies comparing and assessing the verification tools available in today's software market.

Indeed, each construction project is digitally modeled before the work begins. The modeling is over once the digital mock-up has been produced and verified. The model must be buildable and comply with current code construction standards. In particular, manual checking takes a long time, but digital tools allow the checking process to be automatized (Preidel & Borrmann, 2015). This is especially beneficial because incorrect modeling and design issues lead to additional costs.

Even though model checking appears to be the most important BIM requirement, the shortage of studies about the different checking tools' characterization is of some concern. In this paper, we propose a precise comparison of four BIM-based model compliance checking tools: Dynamo, Grasshopper, Navisworks and Solibri Model Checker (SMC).

We start by reviewing related works comparing BIM tools and works on model checking systems. The methodology, the statement of purpose and the main objectives of this paper are then elaborated. We summarize the results of the two comparative analyses, and finish with a discussion about the results.

2 Related works

In the relevant literature, many studies focus on BIM adoption or BIM coordination, but very few deal with digital model checking software. Below are some of the related works about BIM tools and model-checking.

2.1 General BIM tools comparison

The recent literature offers some comparative studies of BIM tools. For example, Muñoz and Arayici compare free BIM coordination tools to help Small and Medium Enterprises to better adopt BIM (Muñoz & Arayici, 2015). They highlight the main characteristics of BIM tools summarized into three categories: features, interoperability and usability. Hittier et al. present a whole guide formalizing 3D BIM coordination best practices (Hittier, Boton, & Forgues, 2018). Via surveys, the guide shows which tool's functionalities are the ones most expected by users and AEC employees, most of which are functionalities for checking tools. Mehrbod et al. focus on the characterization of design issues and discuss software system's expected functionalities (Mehrbod, Staub-French, Tory, & Mahyar, 2015). Their proposed framework indicates different categories of modeling issues leading to rule checking specifications.

2.2 BIM-based verification tool comparison

Nevertheless, few studies compare or even assess the available checking tools. Hjelseth presents the current development and the potential in BIM-based Model Checking (BMC) (Hjelseth, 2015). Its use would be one of the BIM maturity indicators, and the author declares that interoperability must be improved for BMC to become standard. Digital clash detection helps in the traditional quality assessment of drawings; BMC becomes interesting when one has to manage a huge number of elements. Today's clash detection appears to be too rough and not accurate enough. Some deplore the poor quality of models, which hinder the process of good digital checking. Moreover, there is the current challenge to convert design rules and regulations into digital rules (computable rules). More specifically, Kincelova et al. evaluate eight different checking tools in terms of code compliance checking applied to fire protection (Kincelova et al., 2019). Their results suggest that the existing code checking solutions fail to meet the fire protection challenges because of its specific.

2.3 Mockup design quality checking

Messner in Version 3.0 of the BIM Project Execution Planning Guide suggests four steps to review a design model (Messner et al., s.d.) :

- Visual Check: Ensure there are no unintended model components, and that the design intent has been followed by using navigation software;
- Interference Check: Detect problems in the model where two building components are clashing by means of a Conflict Detection software system;
- Standards Check: Ensure that the model is done according to the standards agreed upon by the team; and
- Element Validation: Ensure that the dataset has no undefined or incorrectly defined elements.

This classification is intended for model quality checking (Messner et al., s.d.). It evaluates the design quality: is the mockup's quality sufficient to properly operate the model? However, those criteria do not evaluate the model's constructability or its built regulations compliance.

2.4 Model checking process management

Some classifications of BIM-based model checking concepts can be found in the dedicated literature. Hjelseth suggests the following four types of checking according to the nature of their outcome (Hjelseth, 2016), as listed below:

- validation checking (pass/fail);
- model content checking (a filtered list);
- smart object checking / integration (a modified model); and
- design option checking / guidance (options and advice).

Different types of checking are linked to different types of outcomes. According to the category to which a rule belongs, the rule checking tool will have different needed features.

Others have proposed levels of BMC: here are the five levels of BMC maturity proposed by Hjelseth (Hjelseth, 2015) according to Succar studies published in 2009 (Succar, 2009):

- Level 1 Clash detection checking;
- Level 2 Adjusted model checking;
- Level 3 Specific purpose checking;
- Level 4 Integrated model checking;
- Level 5 Pervasive model checking.

The various levels indicate that BMC offers multiple checking options from clash detection to advanced code compliance verification. Such multi-level categorization leads us to think that level n + 1 necessarily includes level n, but this has to be verified. Heljseth describes these levels in a 2-axis matrix (Hjelseth, 2015). This classification based on those two axes, digital rule complexity and the quality of the model's digital data/information, suggests that BMC levels are dependent upon these two aspects. If the former depends upon what you want to verify, the latter depends upon the model on which you want to do the checking. It is obvious that for each project those parameters may change. This classification helps us to assess the checking possibility of each tool.

3 Methodology, statement of purpose and objectives

Given the lack of studies concerning these tools, we propose a global comparative analysis of the four main commercially available digital verification tools: Dynamo, Grasshopper, Navisworks and SMC. Each one will be evaluated according to specially-chosen criteria. This paper's comparative study seeks to help designers and digital modelers in their choice of BIM checking software.

First, we proceed to a general comparative analysis, Comparative analysis n°1, of the four tools. From the literature, we identified 27 relevant tool functionalities as criteria, divided into three categories: main features, interoperability, and usability. In the second step, we study the BIM-based model checking possibilities of each solution in more detail, Comparative analysis n°2, in which we compare what can be checked and how it can be checked on the different tools. In parallel, this process allows us to better know the software systems: how they download, DMU test, etc. Obtaining functional digital models took considerable time and effort. We manipulated three models: a standard educative one, the model of a massive timber condominiums complex constructed in Montreal in the early 2010s and the associated MEP model. We have received authorizations from the companies to use their models. The comparative analyses grid (See Tableau-A I-1 and Tableau-A I-2), show the results from our experiences with the tools. We conclude with the benefits of each tool and its most appropriate uses. We finish with a discussion about the results.

4 Results of the comparative analysis

4.1 Checking tools selection

We choose to compare the four main commercially available digital checking tools: Dynamo, Grasshopper, Navisworks and Solibri Model Checker (SMC). The two first are plugins from the two software systems, Revit and Rhino, respectively; they function by visual programming. Navisworks and SMC work with the partial modification of existing rules and rulesets. More details are presented below.

Dynamo is an open-source visual programming plugin from Revit. It is used to generate an automated structural design with generative curves. Dynamo can be used as a geometric checking tool in creating visual programming scripts that check or compare dimension ratios from model components. Thanks to its use of cursors, input and output block visual programming is user friendly. Grasshopper is a visual programming plugin from Rhinoceros 3D. It runs fairly similarly to Dynamo. Navisworks Manage is used for design review and virtual inspection to ensure that a model is error-free. Freedom, Simulate and Manage are the three versions of Navisworks software. Freedom is a free viewer for native .ndw files. Simulate is the base level, and includes all the functionalities except for Clash Detective. Manage is the top level of Navisworks and includes all the features. This tool is useful to detect clashes and collisions and for federating models. Solibri is a dedicated rule checking tool. Solibri is the first open BIM-based model checking commercial software. It offers three possibilities: Solibri Office for rule checking (SMC), Solibri Site to extract information and quantities, and Solibri Anywhere to visualize and comment (SMViewer). SMC is a rule-based checking software in which pre-existing rules or rules created from the template in the Ruleset Manager tab are checked in an .ifc model.

4.2 Criteria selection

The tools must be compared according to specified criteria; in this context, the criteria are the functionalities expected by the tools. We find them in the dedicated literature, noted as the expected functionalities by users in surveys or studies. We want the list of tools functionalities to be as complete as possible.

Among the evoked tools functionalities found in (Muñoz & Arayici, 2015), (Hittier et al., 2018), (Mehrbod et al., 2015), (Hjelseth, 2015, 2016), we have distinguished two types; those related to the users-tool interaction and those related to the BMC possibilities. Therefore, we conducted two comparative analyses with these two criterion types.

4.3 Comparing the users-tool experience

The first evaluation compares the general features offered by checking tools that participate in the user experience, a term that describes well the human-machine interaction, better named the user-tool interaction. Most of these criteria are common BIM-tool functionalities, i.e., they are the general possibilities offered by the tools (script python, issues visualization, interoperability format, 3D navigation, etc.). We summarized these criteria into three categories inspired by Muñoz (Muñoz & Arayici, 2015): main features, interoperability and usability. The main features include the different work options of the software system and how each option works. Interoperability relates to the ability to exchange information and communicate with other tools. Finally, usability criteria characterize the ease of use.

- **Main Features.** Both plugins Dynamo and Grasshopper are based on visual programming methods with their node libraries. Nodes are calculation boxes linked to each other with multiple inputs and outputs. Some nodes link the model and the script to extract the required information. SMC is a checking tool based on a large provided library of checking rules. In the Ruleset Manager tab, 55 predefined rules can be partially modified to adjust the checking settings. SMC offers the possibility to generate a .bcf report after checking has been completed. Navisworks has the specificity to enable walk-throughs into a model to make virtual inspections. Both Navisworks and SMC offer the possibility to visualize the issues and the non-compliance instances directly on the digital model. Quantity takeoff is possible in each of these four tools.

- **Interoperability.** All four tools work with the common IFC standard. Concerning the BIM Collaboration Format (BCF), an open file utilized to exchange information like issues or comments: Dynamo, Navisworks and SMC can each generate a .bcf report using a BCF Managers plug-in. The Green Building XML schema ─ named gbXML ─ is a language that facilitates the transfer of data between BIM and AEC analysis software. Often used as an aspect of evaluating model sustainability performance, Dynamo, Grasshopper and Navisworks enable this exchange format. The COBie (Construction Operations Building Information Exchange) extension ─ a non-proprietary data spreadsheet containing non-geometric model information ─ is permitted with the following tools: Dynamo, Navisworks and SMC. SMC is relatively limited in terms of its supported file formats: .ifc and .pdf and .dwg.
- **Usability.** Navisworks and SMC can open multiple BIM files at the same time. With no need for code and script creation, working in these two systems can be rather easy compared to using Dynamo and Grasshopper. In addition, checking results are presented more visually in Navisworks and SMC (colors, highlighting).

The table Tableau-A I-1 below summarizes the comparison results concerning the users-tool experience of the four tools. The checked box means that the software has the feature in question. Blank boxes represent a lack.

Tableau-A I-1 Table comparing tool features and user experience

	CRITERIA	Dynamo	Grasshopper	Navisworks	Solibri Model Checker
MAIN FEATURES	Automated rule checking	X	X	X	X
	Open source	X			
	Visual programming	X	X		
	Node library	X	X		
	Rules library				X
	Information/quantity take off	X	X	X	X
	Code python script	X	X	X	
	Issue visualization			X	X
	Reporting	X		X	X
	Model walk through			X	
	Add colors on the model			X	
INTEROPERABILITY	IFC standard (OpenBIM)	X	X	X	X
	.bcf report generation	X		X	X
	.gbXML interoperability	X	X	X	
	COBie extension	X		X	X
	Direct link to Revit	X		X	
	Direct link to ArchiCAD				X
	Wide variety of readable file formats	X	X	X	
USABILITY	Merge BIM files			X	X
	Clear interface/simple navigation	X	X	X	X
	Simplicity of use (without coding)			X	X
	Easy file importing	X	X	X	X
	Users-friendly results presentation			X	X
	3D navigation (rotate, zoom)	X	X	X	X
	Search function			X	X
	Measurement tool	X	X	X	X

4.4 Comparing the BIM-based model checking possibilities

The second comparative analysis focuses on the BIM-based model checking specifications: for each tool, what can be checked and how can it be checked? This comparison provides new information about the advanced code checking capacities of the tool, i.e., the concrete checking actions and how to proceed.

- **What can be checked?** Among the four evaluated tools, Navisworks is the most appropriate tool to perform clash detection. Code compliance checking consists of examining the model compliance towards the regulation: Dynamo, Grasshopper and SMC enable such compliance checking. In the predefined rules of SMC, it is possible to check the model data consistency, detect any deficiencies and even process an energy efficiency check. The table below may seem to indicate that the SMC system offers the most checking options, but both visual programming tools also offer a wide variety of checking options thanks to their script creation possibilities.

- **How can it be checked?** There are many ways to verify a model's compliance. Both plugins Dynamo and Grasshopper perform rule-checking based on visual programming methods with their provided node libraries. SMC is a checking tool based on a large, provided library of checking rules. Navisworks perform clash detection with inner rules that cannot be modified. This brief overview suggests that Dynamo and Grasshopper are the most flexible tools for rule creation.

The table Tableau-A I-2 below summarizes the comparison results concerning the verification capabilities of the four tools. The checked box means that the software has the feature in question. Blank boxes represent a lack.

Tableau-A I-2 Table comparing the verification capabilities of the tools

	CRITERIA	Dynamo	Grasshopper	Navisworks	Solibri Model Checker
What can be checked?	Geometric rules verification	X	X	X	X
	Non-geometric rules verification	X	X	X	X
	Clash detection			X	X
	Hard clash management			X	X
	Soft clash management			X	X
	Spatio-temporal conflicts (workflow clash)			X	
	Clearance in front of / space checking			X	X
	Code compliance checking	X	X		X
	Direct model BIM validation				X
	Model version comparison				X
	Comparison of ARCH vs the STR model				X
	Checking model data consistency				X
	Deficiency detection				X
	Component check / content checking	X	X		X
	Energy efficiency checking				X
How can it be checked?	Rule-checking with existing rules			X	X
	Rule-checking in modifying existing rules			X	X
	Rule-checking from nodes & visual programming	X	X		
	Flexibility of rule creation	X	X		
	Separate rule sets				X
	Develop new rule sets	X	X		

5 Discussion and conclusion

The results suggest that those four software systems complement each other in every way. All allow automated rule checking to proceed, but in different ways.

Navisworks seems to be the best software with which to review the collision issues and inspect the inner of mockup tanks to the walk-through option. Due to its large rule library, SMC is well suited to check a global mockup; nevertheless, it may be limited because the rule customization process is relatively restricted. On the contrary, both visual programming tools – Dynamo and Grasshopper – offer a wide possibility for rule checking thanks to the customization possibilities for creating their own rules, but it takes time to master coding in visual programming. In terms of interoperability, while they each have their specific native format, they do operate with the Industry Foundation Classes format. Even though Navisworks can utilize multiple readable file formats, this tool has limited checking capabilities. SMC, with its rich database of ready-to-use rule templates, can accomplish much more checking and review tasks than Navisworks. Among these four considered tools, we conclude that Dynamo and Grasshopper, due to their visual programming functioning, offer the most flexibility in rules creation.

Although the proposed comparative approach contributes to highlighting the advantages of these verification tools, it still has several limits. First, we only compare four tools, which means some interesting tools may not have been considered. In the future, it would be worthwhile to extend this comparative study with additional checking software systems, as well as to re-evaluate updated versions of these four. A more detailed comparison between the visual programming plugins Dynamo and Grasshopper (run time, node type, browser, display, etc.) would also be welcome. Continuing with these four checking tools, it might be interesting to concretely illustrate the user functionalities with screen-shots, or to execute the same verifications with each of the tools and to then compare the process.

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