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CRITICAL REVIEW OF TOLERANCE MANAGEMENT IN CONSTRUCTION

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ABSTRACT

The current practice of Tolerance Management (TM) is still very ad hoc and reactive, despite increasing calls for waste reduction and an improved quality of buildings particularly within industrialised construction. This paper aims to identify the root causes of tolerance problems, the reasons why current methods have not been as successful as expected and why the industry still struggles with this issue. Having reviewed and interpreted the existing literature, it is apparent that tolerance problems fall into two categories defined by intrinsic and extrinsic factors. Furthermore, the drawbacks of the existing methods for TM were analysed, and the findings show that none of the existing methods have been considered in a continuous and holistic process and they remain scattered.

KEYWORDS

Tolerance Management, Root Cause Analysis, Industrialisation, Integrated Design and Construction

INTRODUCTION

Following the precedents set by Plato and Aristotle on the study of Geometry, Hugh of Saint Victor was the first medieval scholar who divided this subject into practical skills and theoretical skills, sometime between c.1125-1141. He applied geometrical theories in practical ways and interpreted several structures. This achievement in design specification made it possible to design buildings more accurately, facilitating the setting out the building and checking the finished parts and their relative dispositions (Addis 2007). Since then, there has been a continuous progression in using specifications to generate building designs.

The use of design specifications in manufacturing, including tolerances, has evolved to support design inter-changeability and mass production. Tolerances have a key role in the

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assembly and production process, because parts that are made independently are expected to function coherently with adjoining parts (Creveling 1997). Holbek and Anderson (1977) state that although tolerance specifications in the construction industry have been developed for materials such as steel and concrete, there is little input on the issue of conflicting tolerances at the interfaces between different materials and components. Almost 40 years later, the industry still struggles with the same challenges and the subject of interfacing between components is yet to be resolved.

Designers often do not consider the constructability of their design in terms of tolerance (Alshawi and Underwood 1996) or accommodate this adequately into the design process (Milberg 2006). As a result, contractors often misunderstand the designers' intentions and solutions (Alshawi and Underwood 1996). Moreover, addressing tolerances on site still relies layman knowledge, like the early days of the manufacturing industry (Milberg and Tommelein 2003).

There are many books and published papers in construction that consider tolerance as a minor topic. Few of them extol any improved TM, particularly for its ability to minimise defects. (e.g. Feld and Carper 1997; Sacks et al. 2010). Whilst there are few novel research contributions to this field (e.g. Milberg 2006) there is no evidence to indicate that they are widely used in the industry. The reason might be that they are expressed in a difficult format for the industry to understand, interpret and apply. According to Forsythe (2006), much of the literature on tolerances is based on the participants' perspective rather than empirical data. The existing methods used for TM in construction have been adopted from manufacturing, sometimes even without refinement towards a more relevant application. They lack a holistic and continuous process, even though the improvement of TM needs the development of a method which (1) emphasises the continuous process of improvement and learning from experience and (2) must be holistic which means it must start from the design and continue to the implementation procedures (Seymour et al. 1997). In other words, they are very scattered. Moreover, the use of recommended solutions are often either time consuming (e.g. geometric and dimensional tolerancing) or expensive (e.g. requiring a higher level of inspection) given the current level of technological development in the industry. In fact, there is no single methodology for TM that defines a practical step-by-step approach to developing optimal tolerances from product development to project handover, while balancing the cost for any given design. As a result, TM in the construction industry still remains very ad hoc.

Lean construction concept has been successful in improving building quality and reducing waste. However, TM has not been directly addressed by this concept. In despite Koskela (1992) and Koskela (2000) are amongst the first researches, if not the first, to warn the industry of tolerance problems and highlight the need to address TM, the focus on TM is still missing and tolerance problems seem to be accepted in the industry. Milberg and Tommelein (2003) concur that this is due to a lack of awareness of the cause and effect of tolerance problems, and that the current knowledge of tolerancing is tacit. This paper, serving as an initial output of a PhD research, aims to (1) critically discuss the root causes and consequences of tolerance problems and (2) analyse the two solutions that are considered to be effective for the improvement of TM, namely industrialisation and integrated design and construction. The paper is based on reviewing and interpreting

existing literature. It is envisaged that the findings will be developed further using empirical data.

TOLERANCE MANAGEMENT IN CONSTRUCTION

All materials and elements in the construction industry have their own dimensions and their position is specified on drawings. In reality however, elements and materials cannot be exactly level, plumb, straight, and positioned as they were designed. “*The accepted amount of this variation is the tolerance of the material or installed position of the material*” (Ballast 2007). The construction industry primarily requires an understanding of new terminologies related to tolerances: TM, tolerance problem, tolerance failure, and tolerance incompatibility are the terms that must first be explained. According to Milberg (2006), TM is about utilising various tools and methods in order to (1) attain the highest conceivable quality and performance to deliver the maximum value and (2) to avoid any interruption of flow due to tolerance-related problems to minimise the waste.

Regarding *tolerance failure*, the term failure itself is often defined as a human action that exceeds some limit of acceptability. Feld and Carper (1997) speculate that failures result in catastrophic consequences when there is nonconformity with design expectations. An example of failure is structural collapse that is often followed by dispute and litigation. Tolerance failure can thus be defined as an unacceptable deviation from specified tolerances that result in catastrophic consequences and require costly and time consuming re-work. *Tolerance problems* can be perceived as performance problems that are less catastrophic and can be remedied without laborious rework. The term tolerance problem should be used as long as the accentuation is not on deviations that dramatically damage structural integrity or performance capability. According to the American Concrete Institute (ACI) Committee (1990), *tolerance incompatibility* refers to the interface of two materials with different levels of dimensional accuracy. An example of tolerance incompatibility includes the interface between metal curtain walls or partition walls with structural frames.

The construction industry is unique in that tolerances range from thousands of an inch for many manufactured items to several inches for many field installed components (Ballast 2007). This is because the construction industry is currently in a difficult transitional state, between being either craft-based or industrialised (Koskela 1992; Douglas and Ransom 2007). Some elements and materials that are produced off-site such as glass, timber, and steel have a high level of dimensional accuracy while it is difficult to reach precision in other components such as in-situ concrete elements (Koskela 2000). In order to achieve a tight fit between these two types of components, the industry often relies on received tradition (Milberg and Tommelein 2003) using filler materials (e.g. mastic, foam, cork) and grinder.

Even though tolerance problems can be proactively eliminated in the design stage, they are predominantly identified during the inspections and corrected in a reactive manner. Responding to tolerance issues in a proactive rather than reactive manner requires (1) the identification and elimination of the root causes (Meiling et al. 2014) and (2) an understanding of the severity of the consequences of the tolerance problem, in order to take

appropriate preventive actions. These two factors are intrinsic parts of a continuous improvement process.

ROOT CAUSES OF TOLERANCE PROBLEMS

Current literature identifies few categories of the root causes of tolerance problems. For example, Seymour et al. (1997) argue that tolerance problems should not be seen as root causes of sporadic defects, but chronic defects. They speculate that current conventions are not effective for tolerance management. Milberg (2006) divides the root causes of tolerance failures by analysing case studies into the following six tolerance failure modes: multiple interpretations of tolerance specifications; incomplete or missing tolerance specifications; standard process capability & tolerance specification mismatch; poor workmanship/below standard process capability; functional, fabrication, construction & inspection tolerance specification mismatch; and inconsistent tolerance loop. Jingmond and Ågren (2015) believe that tolerance problems are due to both exogenous factors (manufacturing tolerances) and endogenous factors (positioning tolerances).

Having reviewed and interpreted the existing literature, it can be concluded that tolerance problems are the result of a complex interplay of extrinsic and intrinsic factors. Intrinsic factors are more related to processual causes, while extrinsic factors are more related to technical causes. This categorisation shown in Tables 1 and 2 give a concise view of the root causes of tolerance failures in the industry, encompassing all former categorisations. However, the list is not exhaustive and needs to be developed based on more empirical data.

CONSEQUENCES OF TOLERANCE PROBLEMS

The consequences of tolerance problems result in two key aspects: (1) incurred defects and chains of waste, and (2) an unsatisfactory performance of the building.

Defects and chains of waste: Tolerance problems are considered as one of the root causes of defects both in manufacturing (e.g. Henzold 2006) and construction (e.g. Seymour et al. 1997; Jingmond and Ågren 2015). Defects result in rework which in turn often cause more errors incurred by operatives, variation in project scope or quality, time and cost overrun, and dissipation of human resources (Love et al. 2009). According to Koskela et al. (2013), the effects of waste remains in a process and causes further waste. When investigating one specific waste, it must not be considered singularly, but rather as a “*chain of waste*” that can be caused. Hence, tolerance problems not only cause defects but also create chains of waste. For example, such problems in structures may affect structural integrity, as well as operating capability or abutting components (Milberg and Tommelein 2003). Tolerance problems and the following chains of waste have indirect and adverse cost impacts due to the deterioration in quality of related activities, longer project lead time (Milberg 2006), and incompatibility of tolerances in the end product with standards and contractual agreements (Forsythe 2006). They also have direct impacts as a result of the cost of the rework (Milberg 2006). Moreover, tolerance

problems impact the customer satisfaction and are often at the centre of disputes between the consumer, contractor, supply chain, and Client (Forsythe 2006).

Table 1: Root causes of tolerance problems

Factors	Description
Lack of standardisation	<p>Standardisation is essential to establish 'lingua franca' to enable co-operation between different actors involved in a project (Star and Griesemer 1989). Design teams are often unaware of the circumstances and working systems on site due to a lack of co-operation followed by a lack of standardisation. This shortcoming often results in sloppy designs with tolerances that are either overly restrictive or lenient.</p> <p>Documentation is one of the most important aspects of standardisation. The industry has difficulties in capturing, storing, sharing and re-using all the information and knowledge relating to and arising from a construction project, assuming that it exists, but much of it is never produced (Shelbourn et al. 2006). Indeed, there is no widely accepted systematic documentation mechanism to encourage control and review process, propagate new knowledge, and share best practices (Roy et al. 2005) in order to convert the tacit knowledge of TM into explicit knowledge and avoid repeating the same mistakes in design and on site. Documentation can eventually lead to establishing a repository which foreshadows both extrinsic and intrinsic causes of tolerance problems.</p>
Poor workmanship	<p>Poor workmanship is a typical source of tolerance problems and refers to performing tasks that do not comply with a design specification (Milberg 2006).</p>
Lack of state of the art	<p>Unlike manufacturing, the construction industry has no widely accepted method for developing and optimising tolerances which serve a key role in quality, accurate fit in the assembly process, cost, and cycle time of end products (adopted from Creveling 1997), although there have been advances in design process to communicate tolerances (e.g. Ballast 2007; Milberg 2006). Optimal tolerances lead to obtaining maximum component function and correct fit in assembly processes.</p>
Incomplete drawings	<p>Drawings with incomplete or wrong tolerance specification may result in deficient connection details, selection of incompatible materials or assemblies that are not constructible (Feld and Carper 1997), uncertainty on site, tolerance problems, and rework (Seymour et al. 1997). Uncertainty here means when contractors do not know how to fit components, and deal with interfaces.</p>
Inefficacious standards on tolerances	<p>Current construction techniques require the use of a combination of factory-built and site-built components assembled in complex ways. It is more important than ever to refer to standards and understand what normal tolerances are, how they can accumulate during construction, and how to plan them before they cause problematic issues (Ballast 2007). However, standards on tolerances are not widely considered in the industry and tolerances are often replicated from similar previous drawings (Mavrikas et al. 2015). The following reasons are the main drawbacks of tolerance standards: (1) there are still many construction tolerances that do not exist as industry standards (Ballast 2007); (2) standards are often based on consensus opinion of the committee participants, not on empirical data (Milberg, 2006). Hence, they are unable to specify functional requirements when annotating a drawing (Mavrikas et al. 2015); (3) there are different versions of standards and sometimes companies have their own internal standards. Dissonance in standards incurs tolerance problems when using different standard systems (ACI Committee 1990).</p>

Lack of education Students receive rudimentary education for tolerancing. In fact, tolerancing is perceived to not be teachable in school but only trainable on site while Feld and Carper (1997) argue that “*education is an essential component of any failure mitigation strategy*”.

Table 2: Extrinsic Factors

Factors	Description
Materiality of elements	Seven scenarios are probable for materials and components in the realm of tolerances: (1) they may not meet the specified dimensional tolerances and have a poor quality, (2) adjacent components lack a uniformity of dimensional accuracy (Koskela 2000), (3) all materials exhibit reversible or permanent dimensional changes as a result of physical (e.g. stresses) or chemical causes (BS 6954-1 1988), (4) tolerances specified for a manufacturer may be either unreasonably tight and increase the production cost of components or they are loose and remedial actions must be taken to ensure components will fit properly, (5) a lack of information on dimensional tolerances of components made either in factory or on site, (6) critical dimensions of all components may not be inspected in a factory setting, and (7) components may become distorted during transportation to site, while components are often measured on site only visually and it is unlikely to recognise out of tolerance components prior to the process of assembly.
Undeveloped/ Expensive Technology	BIM and advanced measuring instruments are new technologies that can greatly contribute to TM process. BIM enables better control of spatial dimensions and tolerances (Sacks et al. 2010), 3D modelling of interfaces, detecting physical clashes of components, receiving tolerance specifications from manufacturers and assigning them to components, and comparing as-designed models and as-built models to measure deviations from specified dimensions. However, BIM is not sufficiently developed to automatically assign tolerances to components; detect the tolerance incompatibility of adjacent components; analyse required joint capabilities to mitigate the effects of tolerance problems; consider added thickness due to fire proofing spray and grout, inevitable dimensional variations resulting from movements and changes of size of materials, and etc.; and accumulate tolerances and assign real tolerance values that consider the worst case in which component dimensions are at their tolerance extremes or component members are placed at the extreme location allowed by the stated tolerances. Measuring instruments which have a higher level of accuracy are often more expensive and unaffordable compared to conventional instruments.

Unsatisfactory performance of building: Depending on their severity, tolerance problems may affect the performance of the completed building by: (1) producing eccentricities of loading, reducing areas for load bearing, inducing stresses and damaging structural stability (BS 6954-1 1988), (2) damaging the appearance of the building aesthetically (BS 6954-1 1988), and (3) creating poor indoor conditions such as acoustic problems, and issues with flat and level surfaces.

EXISTING METHODS FOR TOLERANCE MANAGEMENT

Two methods are often proposed for the improvement of TM. The benefits and drawbacks of each are discussed below.

INTEGRATED DESIGN AND CONSTRUCTION

There is a general consensus on the need for integrated design and construction, as site problems are mostly caused by poor integration (Alshawi and Underwood 1996). Integrated design and construction helps to eliminate tolerance problems proactively at the design stage, while a lack of coherence between design and construction results in quality problems. However, Minato (2003) states that the industry tends to focus on failures including tolerance problems only at task or activity level and then corrects the defects on site. This is because:

- although the industry's recent trend is to incorporate all details in the design to reduce the problems on site, this action does not necessarily result in better performance (Love and Josephson 2004). Spending time on inspection and co-operation in design can sometimes cost more than dealing with them on site. To overcome this problem, the ACI Committee (1990) suggests that statistical analysis is required to (1) balance the cost of correction and customer dissatisfaction against the cost of precision layout and a more rigid tolerancing process, (2) make decisions on having tighter tolerances against wider joint flexibilities in components, and (3) optimise the construction cost by revising the design specifications.
- designers traditionally neglect continuous improvement in design (Koskela 2000), even though this is imperative for improved TM.
- as implied earlier, tolerance problems affect the quality of the end product while less attention is paid to quality management during the design stage, and designers presume common practices will remedy the problems (Love et al. 2009).
- designers are under the pressure of tight schedule to finalise designs.
- designers are perceived to be responsible for addressing the tolerance problems. (Alshawi and Underwood 1996). However, they lack the understanding of site conditions, tolerance incompatibilities, and design constructability.

Construction input into the design process (integrated design and construction) is necessary to reduce tolerance problems (Alshawi and Underwood 1996). There are two preconditions to accomplishing integrated design and construction, and improving TM:

- (1) establishing a continuous process that aims at mitigating tolerance problems, optimising tolerances, and improving quality systems, design process and legal systems (Minato 2003). The process must be holistic, which means it must be initiated at the early design and must continue throughout the project until handover;
- (2) using an IT-based system which enables designers to test the constructability and impact of their design on the construction process (Alshawi & Underwood, 1996), to simulate interfaces between elements and predict their performance (Kieran and Timberlake 2004), and to generate designs that include reasonable tolerances.

BIM tools are comprised of both of the aforementioned preconditions. It is envisaged that they can potentially reduce tolerances in the factory setting and minimise tolerance problems during production. However, BIM is in its early stages of development in the field of TM and needs to be developed further to fully incorporate both preconditions.

INDUSTRIALISATION

Industrialisation aims at remedying the chronic problems in construction (Koskela 2000) in order to change the culture that ignores waste (Roy et al. 2005). Although the concept of industrialisation has demanded much attention recently and been widely propagated through the industry, Koskela (2000) believes that it is yet to be successful. Applying industrialization to the construction process, with the aim of converting a conventional process into manufacturing, does not necessarily remedy the current problems (Koskela 2000), and can in fact exacerbate the situation. In other words, industrialisation is often considered only as a way of manufacturing components in factory. But it is primarily about establishing effective processes that are adopted by the workforce to streamline activities, improve efficiency and quality (Roy et al. 2005), and move from being project-based towards a process that takes continuous improvement into account.

Although industrialisation is perceived to reduce the interface and tolerance problems (Holroyd 2003), this technique has four drawbacks that impede the improvement of TM:

- (1) since the manufacturing process itself can create much waste (Koskela 2000), factory-production does not necessarily mean a zero tolerance problem.
- (2) industrialisation of some sectors has been faster than other sectors and accordingly some sectors have a higher dimensional accuracy. This misalignment between different sectors results in adverse consequences, particularly when these two types of elements are assembled besides each other (Koskela 2000). In this situation, it is vital to provide adequate control, extensive training, and an effective feedback process to identify potential problems and avoid concealing any such issues.
- (3) even though standardisation aims at reducing variability and uncertainty on site, this technique can itself sometimes increase both of these. Components are produced in factories, independent of the final building's design. Tolerance specifications are not communicated to the design team to make a decision for dimensional discrepancies and to anticipate the impact on adjacent components. As a result, tolerance incompatibilities are very probable. Therefore, industrialisation requires an effective co-operation between the manufacturer, design team, and on-site contactor.
- (4) although repeated processes help to reduce tolerance problems, a lack of feedback from the workplace on how components are fitted into the process prevents maximised improvement and reduction of tolerance problems (Holroyd 2003).

- (5) Industrialisation requires a high level of control over dimensional accuracy while industrialised construction suffers from poor control during both the design and prefabrication stage (Koskela 1992).

CONCLUSION

There is no single TM methodology used in industry, which is widely accepted and applied from the early design stage through to implementation and project handover. To improve TM, it is vital to understand and document the causes of tolerance problems. This paper suggests a concise categorisation for the root causes of tolerance failures, which includes both extrinsic and intrinsic factors. Furthermore, improved TM demands the consolidation and refinement of existing methods and an evaluation of their appropriateness based on feedback from empirical data obtained from industry. After all, the proposed methods must be incorporated into a continuous, standardised, and holistic process that systematically reduces the number of identified problems. Integrating construction input into design and industrialisation are imperative for establishing such a process, although they have their own drawbacks. In addition, the emergence of new technologies such as BIM provides strong opportunities to advance this field, although it still necessitates further development. Raising consciousness and awareness within the industry of the adverse consequences of tolerance problems, and balancing the cost of improved TM against the cost of customer dissatisfaction should not be neglected as these can revise the current perception of the importance of TM for the industry.

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