

PRODUCT AND PROCESS COMPLEXITY IN CONSTRUCTION: AN EXPLORATORY STUDY USING BILL-OF-MATERIALS (BOM)

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ABSTRACT

Modularity has been applied in the automotive and computer industries to simplify production and supply chain management. Instead of coping with dozens of hundreds of parts, these are grouped into modules produced and delivered by suppliers, simplifying products assembly. Bill-of-Materials (BOM) is a technique used in manufacturing to map the modules that form a product at distinct hierarchical levels. Yet, to the best of our knowledge, such technique has not been widely explored in construction to assess the complexity involved in buildings production. This paper uses BOM in an empirical case (a house of approximately 400 square meters built in Southeast region of Brazil) to analyse (i) the total number of different modules forming a building and (ii) how these modules are distributed throughout the work packages for producing such building. The results show that the studied house is formed by (at least) 522 different modules, which are unevenly distributed across 18 work packages. Some work packages (e.g. concrete pillars and walls) have more than 200 modules whereas others (e.g. foundations) have less than 10. This suggests the potential for repackaging and organizing the delivery of modules as kits to ease production tasks.

KEYWORDS

Complexity, modularity, modules, work packages, work structuring

INTRODUCTION

Simplifying production and supply chain management is a core underlining reason for the adoption of product modularity in the manufacturing sector. Instead of coping with dozens of hundreds of product parts these are grouped into modules (sets of parts), which are produced and delivered by suppliers, simplifying the final product assembly. Baldwin and Clark (1997) report that the complexities of a vehicle require car manufactures to control a network of hundreds of suppliers in addition to a complex schedule and a large inventory as buffer. Thus, instead of managing the entire network of suppliers for producing each individual part, parts are organized and delivered as a smaller set of modules (e.g. Doran et al. 2007; Ro et al. 2007). An example is the cockpit module that includes several parts (air bags, heating and air-conditioning systems, etc), which is produced and delivered by a supplier responsible for coordinating the chain of suppliers involved in producing this module (Baldwin and Clark 1997).

Bill-of-Materials (BOM) describes the structure of a product in terms of its constitutive parts (termed here as modules) with the goes-into-relationship (also known as a parent-child

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relationship) among them (e.g. Chung and Fischer 1992, Cox et al 1992, Olsen and Saetre 1998, Matías et al 2008, Kashkoush and ElMaraghy 2016). BOM can be used to assess the extent to which the modules delivered are more or less aggregated and also the number of hierarchical levels that comprise a product architecture. Indeed, as recognized in the literature, modularity of a product and its constitutive modules can be analysed at distinct hierarchical levels. For example, Fixson (2005) examined such hierarchy from a functional viewpoint (namely, the functions performed by the product parts). He argues that the function of a hair dryer (the set of all components forming the product) at the highest level is to dry the hair whereas at the lowest level (of a single part such as screw), might be to hold part B in position C. Thus, not only functions (but also the corresponding physical parts or components performing them) can be analysed at distinct levels.

Inspired by the manufacturing industry, the construction sector has adopted information structures relying on BOM (Hussamadin et al., 2020). Most papers on the construction field related to BOM address (i) Building Information Modelling (BIM), or other technologies, to BOM management (e.g. Zhang, 2022; Song and Fischer, 2020; Mukkavaara et al., 2018; Botton et al., 2018; Song et al., 2017; Genge et al., 2015; Scheer et al., 2014) or; (ii) BOM focused on construction sustainability, such as life cycle assessment (e.g. Tavares and Freire, 2022; Roh et al., 2019; Zea Escamilla and Habert, 2017; Al-Ghamdi and Bilec, 2017) circular economy (e.g. Gillott et al., 2023), replacement of materials (e.g. Ortlepp, 2019; Zea Escamilla and Habert, 2017; Milaj et al., 2017), and other topics (e.g. Songcayauon, 2018; Winistorfer et al., 2005). Yet, these studies do seem not examine BOM from a product modularity viewpoint and their implications from a product and process complexity.

This paper seeks to address this gap by presenting an initial exploration on this theme. It aims to provide initial answers to the following questions: *How many modules (or physical chunks) form a building? How are these modules distributed throughout the work packages? What insights can be gained by connecting the modules forming a building (product view) to work packages (process view)?* In line with Da Rocha and Kemmer (2018), modules (identified in this study by applying the BOM technique) and work packages, refer respectively to the organization and breakdown of (i) a product and (ii) a construction process. Work packages are the outputs of work structuring, and define the organization of work chunks (namely, in what chunks will work be assigned to a production unit, release to the next production unit, in what sequence, etc) as detailed in Ballard (1999).

BILL-OF-MATERIALS

All modules that form an end product pertain to a hierarchical level, or in other words, every product can be decomposed into modules, which can be further decomposed into lower levels modules (Pahl and Beitz, 1996). The level to be considered can be defined according to the assembly sequence or the function performed by the modules and how it relates to the end product (Chung and Fisher, 1992). The hierarchical level is higher as it gets closer to the final product and its main function; therefore, the highest level is the entire product. The notion of decomposing a product in hierarchical levels has been presented in a number of early studies (e.g. Alexander, 1964; Christensen, 1992; Gulati and Eppinger, 1996; Simon, 1962). A technique that maps the assembly sequence of a product (and thus, the modules comprising such product at each level) is the Bill-of-Materials (BOM) (e.g. Chung and Fisher 1992, Van Veen 1992, Jiao et al 2000). In its simplest form, the BOM is a list or a visual display (e.g. tree map, fish bone diagram, list, etc) of all modules (raw materials, components, sub-assemblies, etc) needed to produce an end product.

The modules and how these should be connected are presented through goes-into-relationship (or a parent-child relationship). The “parent” is an (i) in-between product (grouping of modules at a particular level) or (ii) the end product, and the “child” are the modules forming

either one of these. For example, in Figure 1, “prefabricated beam” (at level 1) is a parent for all the subsequent modules (at levels 2, 3, etc). “Concrete” is a child for the “prefabricated beam”, but also a parent for “grit”, “gravel”, “cement” and “water”. Note that “grit”, “gravel”, “cement” and “water” are also a child for the “prefabricated beam”, but in a lower hierarchical level. Figure 1 shows the parent-child relationship in list (a) and tree (b) formats. In the former such relationship is elicited via codes (numbers), whereas in the latter it is through lines connecting the modules at distinct levels. Such codes are not often used in trees representations (Van Veen, 1992). Yet, numbers are usually included to express the volume of modules at each level (Erens et al, 1992; Hegge, 1992; Van Veen and Wortmann, 1992; Stonebraker, 1996; Romanowski and Nagi, 2004, Liu et al, 2014). Distinct information elements can be presented in a BOM such as product definition, manufacturing instructions, engineering changes control, service parts support, liability or warranty policy, order entry facility, costing, and pricing (Mather, 1987). Yet, such technique can also be adapted as needed. Here it is used to map the number of different modules (but not volume) at levels 1 and 2, considering the building assembly or finished product (level 0).

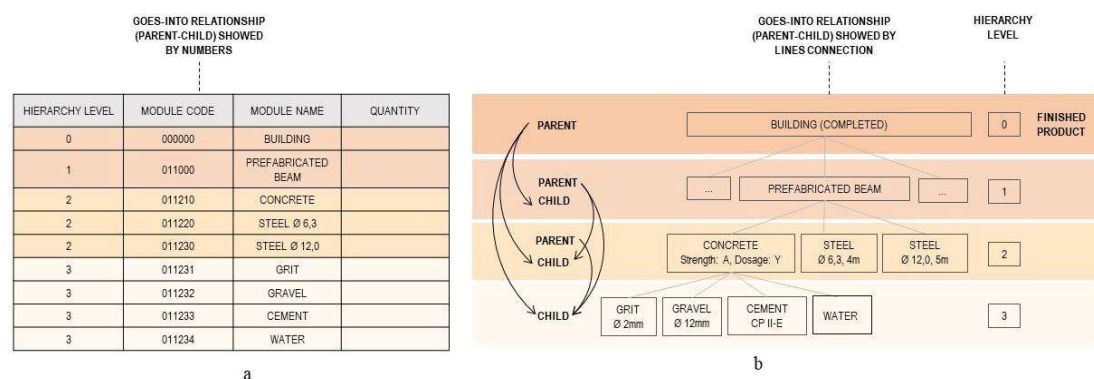


Figure 1: Example Bill-of-Materials as list (a) and tree diagram (b)

To illustrate the applicability of BOM in the construction sector, two examples from the literature are explored comparing BOM off-site (e.g. prefabricated components), more similar to the manufacturing sector, and BOM on-site, which is further developed by this paper. Cao et al. (2022) explore the advantages of BOM combined with BIM, in industrialized construction. Industrialized construction has high degree of repeatability and standardization, such as hotels, affordable housing, schools, hospitals and so forth (Bertram et al., 2019; Cao et al., 2022). This enables a trustful BOM, which in turn enables reliable management of resources. The referred authors propose a module library, using as a timber panelised building as an example. They argue that BOM is the key to information system, offering data with regards to designing, ordering, building developing, construction and maintenance. The BOM complements the BIM application, since BIM by itself is not capable of automatically manifesting the effect of a design change, unless the change violates a rigid constraint, such as a clash.

On the other hand, Hussamadin et al. (2020) highlight that construction is an ongoing process, unlike the assembly line in manufacturing production, in which new spaces are becoming available while work is being finished, leading to a more complex and dynamic relation between such process and the BOM. The authors explore five construction assets in three construction companies, showing that among the variation in workflow, more specifically, the space as the non-movable component, is a challenge of applying BOM to on-site construction and which makes the applicability of BOM more complex. Their study proposes some adaptations of such tool, highlighting the relevance of studies that adopts BOM applied to in-site construction, such as this one. Both studies (Cao et al., 2022 and Hussamadin et al.,

2020) show that the complexity of the products (hereby understood as a high number of modules present in the final product) and assembly system can be assessed by the BOM. Such tool can provide support to management decisions by showing where the source of complexity arise from and help to rationalize the choice of product features and design alternatives. BOM involving can help assess complexity a priori without the need to for detailed information on the constructive system but instead just by looking at the number of modules across the BOM structure.

CASE STUDY

This investigation examined the budget sheet and the production schedule for House A developed by Company B, based in the city of São Paulo (SP), Brazil. Company B has been operating since 2001 and has delivered more than 200 buildings. Most of these are residential houses, but there are also some high-rise buildings and industrial sheds. The company provides a complete solution: it is involved in the product development, including the building design, its production and hand over to the end client. The majority of production tasks are performed by Company B but some such as the foundations and the water heating system are outsourced.

Company B is comprised of an average of ten teams with ten people each. Each team gets a different building to work on which are then swapped across teams. Usually, three people work in the office (the interns work both at the office and at the construction site) and seven in the construction site. The project coordinator, the civil engineer, and a construction coordinator work at the office but visit the construction site regularly. In the construction site are the electricians, hydraulic professionals, painters, etc.

Initially, Company B suggested three houses for this study. House A was selected because it had the most complete budget sheet and had been recently delivered at the data collection time, thus easing potential queries and clarifications around the information gathered. House A is a four-bedroom home with approximately 400 square meters. Besides the common amenities of a house, it also includes parking space for four cars, a gourmet area, a courtyard, and offices. This building was erected using traditional construction methods: cast in place reinforced concrete and ceramic bricks. The construction took place between May 2013 and April 2014.

DATA COLLECTION AND ANALYSIS

First, the budget sheet for House A was sent by Company B via email for its appraisal and assessment. An initial analysis showed that some modules were missing, so receipts for all purchases were requested. These were organized and added to the budget sheet. The first author then performed a one-week visit to the company. During this visit, a one-hour meeting was conducted by the first author with the director, the civil engineer intern, and the building contractor to gather data on the production schedule for House A. Additional receipts and purchase invoices were provided and tabulated, creating a complete budget sheet that produced the results presented in this manuscript.

A second meeting with the same staff was performed to gather data on the company, further details on the production schedule, and to clarify queries regarding some items of the budget. This meeting lasted one and a half hours. The production schedule devised by the first author was based on the realized tasks and actual durations, rather than plans and expected durations previously established by Company B. Thus, the work packages presented here were defined by the authors mainly based on the data gathered in the meetings, the duration of tasks, trades similarities, and crew changes.

RESULTS

The BOM (based on the complete budget sheet) shows that House A is formed by 522 different modules. Considering that a BOM is comprised of several hierarchical levels, the highest is the

complete building (finished product), and the modules (or physical parts) arriving at the construction site (522) are located in level 1. Such number (522) does not entail repetitions (or quantities) for each module, which would be a subsequent step in applying the BOM technique. Some examples of modules include: nail (15x15), cement tile (2,44x0.5 x 4mm), steel bar (CA60 4,2mm 12m), rafter (5x5cm x 2,5m made of cambara wood), batten (2,3x7cm made of cedro arana wood), and batten (2,3x15cm made of cedro arana wood), among others. It is worth noticing that elements that have the same of function (e.g. batten) but have different dimensions (e.g. 2,3x7cm or 2,3x15cm) are treated as separate modules as they are physically different chunks. It is worth noticing that although BOM might resemble Work Breakdown Structure (WBS) in terms of the underlying logic (i.e. a systems' organization in terms of its constitutive parts), the former is specifically focused on the products and its comprising physical parts whereas the latter is more broadly applied to projects and its key stages.

Figure 2 shows the distribution of the 522 modules across the 18 work packages identified in the production schedule for delivering House A. Some modules such as nails, pipes, electric conduits, are used in more than one work package. Thus, the sum of modules in all work packages is 1020 and not 522 (in case each module was used in only one work package). There is an average of 57 modules per work packages yet with a high standard deviation as can be visualize seen in Figure 2. For instance, *WP1 – foundations* has 6 modules whereas *WP5 – concrete pillar and slab (2nd floor)* has 223 modules. Approximately 70% of the work packages have less than 50 modules, with the other 30% (concrete pillars and walls for both floors, fixtures and fittings, and electrical and hydraulic systems) have more than 150 modules. These four work packages (WP3, WP5, WP10, and WP17) account for 76% of the total number of modules. WP3 and WP5 have a large number of modules because rebar and wires arrive as separate items (rather than cut, folded, and pre-assembled kits for columns and beams). In addition, the pipes embedded in the walls also arrive as individual components rather than pre-assembled kits. The same applies to electrical and hydraulic systems; all wires and pipes are also delivered on site as separate components.

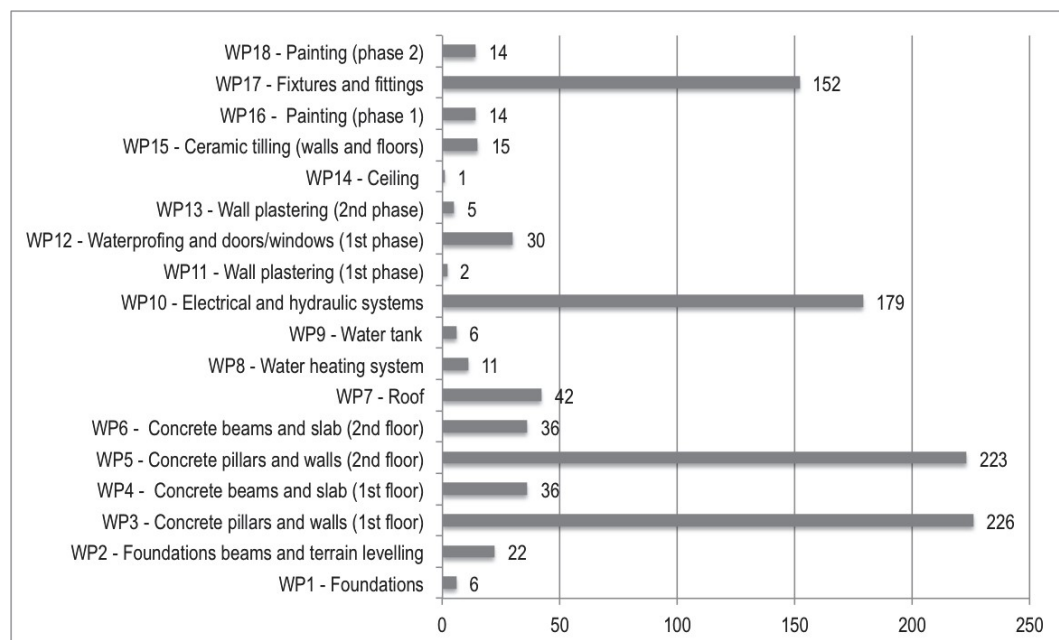


Figure 2: Distribution of modules for House P across the work packages

The 522 modules presented in Figure 2 are level 1 of a BOM (Figure 1), as they are the level immediately below the complete product (level 0) and which refers to the parts arriving at the construction. In this study, the modules at the immediately subsequent hierarchical level (2), namely, the number of parts (or sub-modules) forming each module at level 1 were also analysed. Table 1 shows the number of modules that are formed by two, three, four and five or plus sub-modules at level 2. Because House A is built using traditional construction methods, thus using concrete, steel, wood, bricks, etc (different strength, type, size, etc would be considered modules), the vast majority (79%) does not have sub-modules at levels 2 and below. Indeed, as shown in Table 1, less than one third of the modules is a sub-assembly, namely, has two or more modules at level 2 or below.

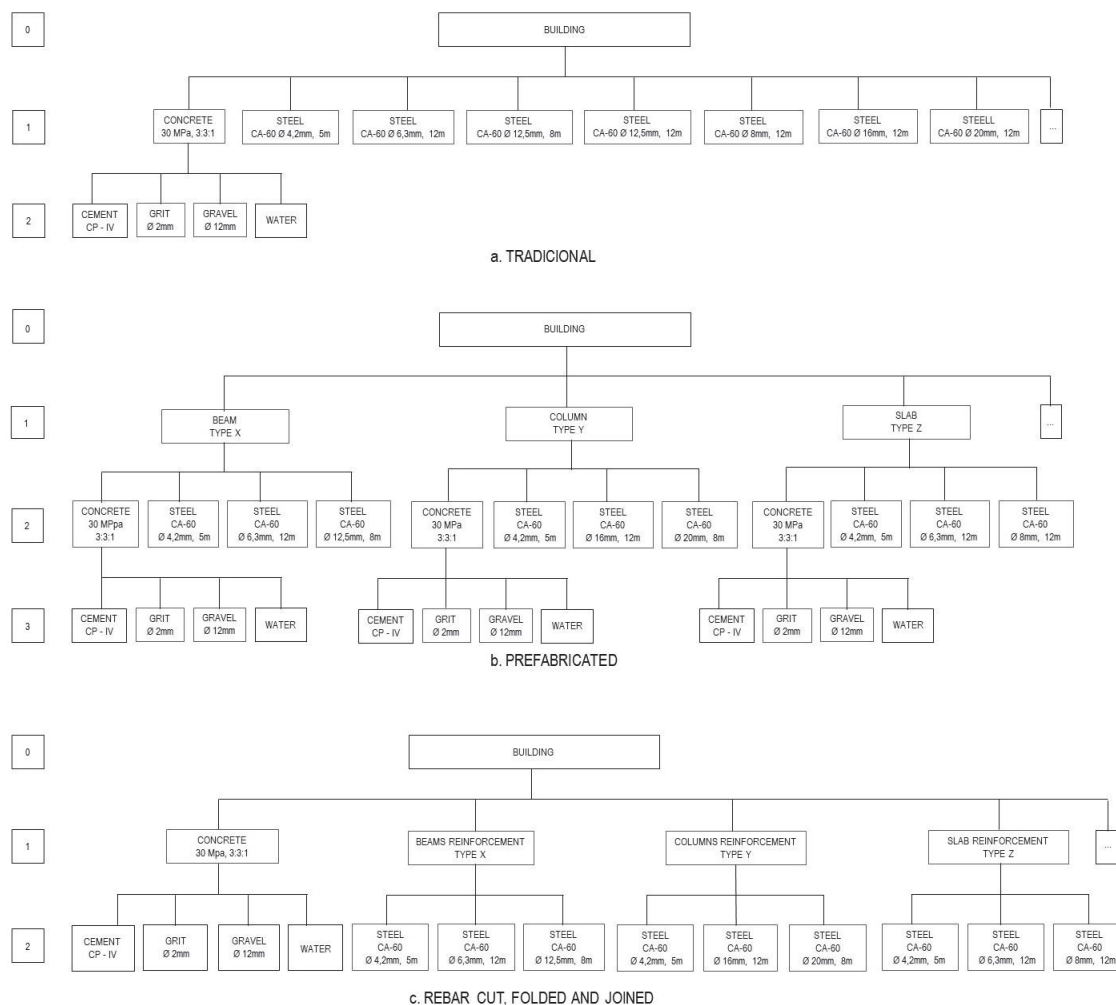


Figure 3: BOMs reflecting different construction methods

Differently, buildings erected using a prefabricated structural system (beams, pillars, and slabs produced off site) such parts (beams, pillars, etc) would be the modules at level 1, and concrete and steel would be modules at level 2 (Figure 3b). this would reduce the product complexity dealt with at the construction site, measured by the number of modules at level (building assembly/erection on site). Opting for prefabricated steel reinforcement would result in an in-between alternative, with a smaller number of modules in level 1 in comparison to traditional construction (Figure 3a): steel parts and concrete would still be at level 1, but with a smaller

number of different modules at this level (Figure 3c). This is because the steel elements would already be grouped into kits, such as reinforcement for beam X, Y, reinforcement for column A, B, etc instead of individual rebars.

Table 1: Percentage of modules at level 1 formed by 1, 2, 3, 4 or 5 or more modules (level 2 or lower)

Number of modules (Level 1)	Number of modules (Level 2 or lower)
411 (79%)	zero
10 (2%)	two
20 (4%)	three
5 (1%)	four
76 (14%)	five or more

DISCUSSION

The total number of different modules delivered at a construction can provide evidence of complexities in terms of product and process (on site production and supply chain). These can be further understood by assessing how these physical chunks are structured and organized by using the BOM technique and linking those to the work packages. This study seeks to introduce a notion already adopted in manufacturing (Baldwin and Clark 1997): to partition a product in modules (or production cells) to simplify production. Indeed, what constitutes a module is determined by the supply chain and the production system arrangement. Namely, a cockpit (and its constitutive parts) is a module (from the car assembler perspective) because it is delivered as a single part (or sub-assembly) to the car assembly plant. Thus, the number and nature of modules that arrive the construction site are tangible manifestations of a production system and supply chain arrangement, regardless of if the decisions around such arrangement have been formally made or not. Such rationale and notions seem underlined when considering prefabrication or modern method of construction.

Yet, they also apply to traditional construction even if the physical chunks are simple materials such as concrete, steel reinforcement, etc as in the case examined here. Indeed, this does not seem to be considered more broadly in construction as also noticed in Da Rocha and Kemmer (2018) under the Modular and Traditional design approaches. Based on the results of this exploratory study, the work packages for producing the structural, hydraulic, and electrical systems contain a large number of modules. These are prime candidates to be delivered as kits or sub-assemblies (rather than as a large set of different parts) to ease and simplify construction on site. This is in line with the principle to simplify by minimizing the number of (product) parts (Koskela 2000). A similar analogy was reported by Feloni (2014) when analysing the LEGO Group in the early 2000s. The number of piece types increased from 6,000 to 12,000 and nearly bankrupted the company (“a nightmare of logistics and storage”), meaning that every LEGO module was so unique that they no longer could be considered a module. In order to save the company, they went back to the previous 6,000 pieces. Therefore, in the construction context, precast elements (beams, columns, or slabs) could be used to reduce the number of modules at the construction site (Figure 3b). Also, pipes could be combined into pre-assembled piping systems.

Fitting and fixtures, which also account for a large number of modules, might not be delivered as sub-assemblies if the building is erected using traditional construction methods. Nonetheless, they can be organized and packaged as kits. For example, having a package with a mix of all the fitting and fixtures modules installed in a given room, rather than stocks

organized based on the module type (e.g. stock of sinks, stock of tiles, etc). These alternatives just described (creating pre-assembled piping systems and per room/zone packing of fittings and fixtures) look at re-organizing the product structure (which can be visualized using a BOM) to simplify production. The counterpart strategy is to re-organize the process, or in other words, to (re-)structured the work packages (e.g. Ballard 1999, Tsao et al 2000). For example, WP3, WP5, WP11, and WP17, which entail the assembly/combination of large number of modules, could be disaggregated in two or more work packages. This would enable the number of modules to be more evenly distributed across production units (i.e. a crew performing a set of production tasks, Ballard 1999) and work chunks (i.e. unit of work handed off from one production unit to the next, Ballard 1999). Clearly both strategies (product and process) can be jointly applied to reduce the number of modules and consequently production and supply chain/logistics complexity.

There seems to be an inverse relationship between (i) the number of modules at level 1 in the BOM and (ii) the number of modules in level 2 and/or lower levels, if one assumes a building is made by a constant/same set of modules, just changing their distribution across the BOM levels. In this study, there is a large number of different modules at level 1 in the BOM so these are not likely to be formed by several modules in level 2 and/or lower levels. This is indeed the case (Table 1): 79% of modules (level 1) are comprised of two or more modules in (level 2 or lower). Conversely, for fully modular buildings (e.g. formed by a small number of volumetric pods) there will be a small number of large modules (i.e. pods), which in turn are comprised by a large number of modules at lower levels. However, it is proposed here that an inversely linear relationship between number of different modules and the level of aggregation of physical part into sub-assemblies (or level of prefabrication) might not apply (Figure 4). Considering the case of a load bearing building erected with bricks, the number of modules for the enclosure system might be close to one (if only a few brick types are used for the entire system). The number of different modules is likely to increase if the system changes to a steel structure and dry walls, as a larger set of different physical parts is needed. Clearly, as the level of prefabrication increases and the building is delivered as a set of fully volumetric pods, the number of modules reduces again (right hand side of Figure 4).

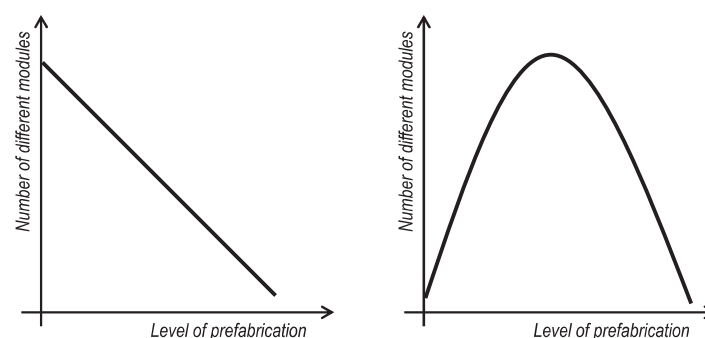


Figure 4: Linear and quadratic functions for

BOM can be used to understand a product breakdown thus also reflecting the complexities involved in operations (procurement, logistics/transport, and on-site construction/assembly). In terms of on-site activities, Tommelein (2006) presents the benefits against the detriments on adopting a modular approach on pipe spool models, which can be generalized for many other components in construction (e.g. doors and windows of various dimensions, supports and fixtures of different types, left- and right-handed mechanical equipment). The referred study shows that as the number of different spools pieces decreases, the production process gets easier. There is potential to a reduction on defects (and thus in rework) with the experienced acquired

on repetitive work; there is less time needed to setup and change-over the production of spools; there is opportunities to facilitate flow, by applying the 5S, using right-sizing equipment and lining up work; inventory and supply chain management is also facilitated through the provision of flexibility in the system. These improvements particularly in terms of overall benefits to the system are created by adopting a modular approach.

Aligned with this finding, a previous study developed by MacDuffie et al. (1996) in the automotive sector shows that the disadvantages due to a lack of modularity goes beyond the costs: in such case greater scope of products variants and options have a significant adverse impact on total labour and overhead hours per produced car, assembly line downtime, minor repairs and major reworks, and inventory levels. In this work, they analysed 70 auto assembly plants worldwide. Further, Su et al. (2010) investigated assembly defects caused by operators mistakes by considering complexity factors such as design. The more similar, or modular the product, the fewer are the mistakes. In the manufacturing, the impact of high levels of product variety on complexity in design and manufacture has been explored through different lens (Roy et al., 2011; Samy and ElMaraghy, 2011; Hasan et al., 2018). This resonates with the findings by Fisher and Ittner (1999). The authors examine the impact of the variety of products on car assembly. The results indicate that the larger the number of modules, the greater the risk of errors, resulting in rework and low quality, mainly due to clustering errors and labour difficulties.

CONCLUSIONS

This paper presents an exploratory application of BOM in construction to assess the number of modules forming a building and how these are distributed across work packages. The results show that House A which is traditionally built is comprised by 522 different modules and that these are not evenly distributed across work packages. Most work packages have less than 50 modules whereas a few have more than 150. As discussed previously discussed, the number of modules seems to be closely connected to the method used and traditional construction might not lead to the highest number of different modules. This is because the modules are essentially simple raw materials or components that can be arranged and adapted in a number of different ways. This prompts an interesting discussion: bricks might be positive from a flow view, by minimizing waste associated with finding the correct part, errors in installing the wrong parts, etc as reported by Tommelein (2006). Yet, they are inefficient from a transformation viewpoint as walls are made by assembling small physical chunks, and which often require cutting and adjusting. On the other hand, a steel structure and dry walls system (proposed as an alternative to the brick system), might have opposing trends for the flow and transformation views just described. Fully volumetric pods on the other hand, seem to reconcile the two views by reducing waste relating to non-value adding activities while also ensuring that transformation is efficient.

This is an initial study looking at BOM and how this technique can be used for assessing product and process complexity. (i) The number of different modules (522) as well as (ii) their distribution across work packages (on average 57 but with a high standard distribution with most work package having less than 40 and some more than 150 modules) are relevant metrics in that regard. Yet, such numbers will become interesting in the context of the numbers encountered for other buildings (including other uses and typologies beyond a two-storey residential house examined here) and construction methods so that overall trends and patterns can be identified. In this sense, this is a truly exploratory as additional efforts (studies similar to this one) doing quantifications are needed to create a database for meaningful relationships and generalizable knowledge to be created around product and process complexity. For example, the hypothetical function connecting number of different modules and level of prefabrications could be corroborated or refuted once sufficient data is gathered and large-scale quantifications studies are completed. Another interesting analysis could be performed by

collecting the data outlined here in addition to the quantity or volume of each different module (data not gathered in this study) correlated with the project performance measure to further provide insights on the impact of complexity. This would complement and expand the findings presented in Tommelein (2006) based on simulation, by having actual project data (the modules used in a project and its actual performance).

Finally, some limitations of this study should be highlighted. First, Company B did not have a clear production schedule and work structuring. These have been defined a posteriori by the authors. Thus, although care was taken in defining the work packages (use of company data, similarity of trade, etc) as highlighted in section 3.1, more reliable results are likely to be obtained for companies with a formal work structuring and schedule. Secondly, the budget sheet used for House A provided by Company B was not complete and had to be updated by the authors based on invoices. Here again, care was taken in gathering all existing receipts to create a complete budget. Also, the budget was scanned to ensure that main items (concrete, bricks, sink, tiles, etc) were not missing, but it is not possible to unquestionably assert it includes all modules. Thus, as an overall conclusion and ballpark figure, it is more appropriate to state that a two story traditionally built house of around 400 square meters is formed by (at least) 522 different modules.

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