Developing work breakdown structure matrix for managing offsite construction projects

Journal:	*Architectural Engineering and Design Management*
Manuscript ID	AEDM-2017-0115.R2
Manuscript Type:	Original Article
Keywords:	Matrix, Offsite Construction, Work breakdown structure, Process

Developing work breakdown structure matrix for managing offsite construction projects

Abstract

Offsite construction techniques continue to receive considerable attention in academic/research discourse. Currently, offsite techniques still require a certain portion of construction works to be conducted onsite; albeit with a significant proportion delivered in a controlled offsite environment - typically in manufacturing facilities. Whilst discourse in seminal literature critique the positive and negative aspects of offsite; on balance, the benefits outweigh the barriers, especially when fully integrated and managed. From a management perspective, the project management techniques typically applied to offsite construction projects typically commence in determining the work breakdown structure (WBS) of these projects. Whilst the WBS approach originated from the manufacturing and engineering domain, this approach is equally applicable to offsite deliverables, reflecting site-based construction activities and concomitant dependencies with the manufacturing processes. However, there are slight discrepancies in processes, and equally, some areas of repetition and duplication. This mismatch has a fundamental impact on integration, creating pockets of confusion, where less seamless (sub-optimal) synergy between offsite and onsite works is lost. This is an acknowledged challenge. Even in cases where the WBS of the manufacturing side was converted into activities to facilitate synchronisation, precise information of the 'product' is still needed. There is therefore a real need to retain the product breakdown structure, particularly the manufactured portion of the works; but, at the same time, ensuring a seamless interface with the onsite works is maintained. This is a challenge. Whilst the WBS-matrix has been implemented in the project management domain to bridge the 'products' and 'activities', this arrangement has not yet been developed for offsite building construction projects. This paper reports an on-going research project set up to implement WBS-matrix for offsite construction projects. Two cases of recently completed offsite construction building projects were used in a case study setting to analyse current practices - to inform the way forward to further develop the WBS-matrix. Findings from this research provide clear guidance for practitioners involved in offsite construction projects; particularly on the development of the WBS-matrix for manufacturing deliverables/activities in order to more effectively manage offsite construction projects.

Keywords: matrix, offsite construction, process, work breakdown structure

Introduction

Stimulated by the need to deal with increasing complexity and specific needs to address time, cost, and quality issues; the Architecture Engineering and Construction (AEC) sector has been challenged to develop new and innovative ways of delivering products and services. This challenge is reported in AEC literature, and is enshrined in many leading global reports and initiatives. More recently, offsite construction has attracted much attention in this respect; the main concept of which is to shift on-site construction activities into an off-site controlled environment (*cf.* product/process delivering and enhanced value proposition). Historically, producing parts of buildings using offsite techniques is not new, having originated in the early 1800's. More recently however, it has attracted increased attention for its ability to deliver bespoke benefits, not least: enhanced efficiencies in the traditional time/quality/cost trichotomy (Sutrisna *et al*. 2017; Goulding *et al*., 2015; Smith 2010). Given these benefits, offsite construction developed a resurgence and was proffered as 'modern method of construction' in the UK (Gibb 1999). Specific advantages of the offsite construction methodology also include a raft of niche benefits, including speed, quality, health and safety, sustainability and life cycle costing (e.g. Steindhart and Manley 2016; Pan and Goodier 2012; Schoenborn 2012). One of the main arguments here is that by shifting a relatively large proportion of the construction activities to an offsite environment (typically in a manufacturing facility), the constructability of the delivery phase can be better envisioned and the delivery itself can be better planned to take place in this controlled environment (Gibbs 1999). Whilst critiques highlight recurrent challenges viz 'mirroring' fragmented practices (cf. coordination and process integration); proponents (on balance), proffer a myriad of solutions for mitigating these negative issues see - Arashpour *et al*. (2018); Khalfan and Maqsood (2014); Pan and Goodier (2012); Pan *et al*. 2007.

The management of construction projects typically follows professional frameworks and industry best practices embodied in official guidelines such as the Project Management Body of Knowledge also known as PMBOK (PMI 2015) or the Projects in Controlled Environment also known as PRINCE2 (TSO 2009). As advocated by both frameworks, one of the most fundamental tools used in these frameworks and guidance is the work breakdown structure (WBS). The WBS has been considered as the standardised method to hierarchically subdivide a project into its sub-parts aiming to reduce project complexity (Hartmann *et al*. 2012; Smith 2010). When implementing the project management techniques in offsite and construction projects, there have been difficulties reported mainly due to the repetitive nature of manufacturing for offsite construction and also the uncertainty and variability of the offsite operations (Salama *et al*. 2016; Harris and Ioannou 1998). From the manufacturing process perspective after a customer order is placed, a WBS of functional components is created to determine the overall production schedule in which each functional component is mapped to its design engineering, production engineering, purchasing and manufacturing (Griess and Restrepo 2011). On the other hand, in executing construction site activities, the construction's WBS typically shows the site activities to be undertaken by the main and subcontractors (Winch and Kelsey 2005). This incompatibility between the WBS systems in the manufacturing based and construction based activities has potentially resulted in a less seamless interface and integration between them, which has been considered as one of the weaknesses and hence criticisms of the offsite construction projects (Arashpour *et al*. 2018; Arif *et al*. 2012). Attempting to address this issue, the research project reported here proposes WBS-matrix especially developed for offsite building projects as the potential solution. The use of WBS matrix to provide a systematic breakdown of the project into smaller components by recognising both product and activity views of the project has been considered beneficial in managing the project (Chua and Godinot 2006; Godinot 2003). Thus the findings of this research are expected to provide guidance for practitioners involved in offsite construction projects to develop WBS matrix to manage offsite construction projects in a more holistic manner.

Literature Review

Off-site construction is one of the many terms referring to the prefabrication of building components constructed or assembled outside the construction site followed by the installation of these components into their final position on site (Ramaji and Memari 2018; Pan *et al.* 2008). Examples of other terms to describe similar constriction methodology include offsite manufacturing (e.g. Blismas and Wakefield 2009), off-site prefabrication/production (e.g. Kale and Arditi, 2006) or industrialised building (e.g. Jonsson and Rudberg, 2013; Kamar *et al.* 2011). In terms of industrialisation in the construction field, prefabrication is merely regarded as the first level of industrialisation before mechanisation, automation, robotics, and reproduction (Richard, 2005). Previous research has identified positive correlation between the extent of prefabrication and the time/cost performance of the offsite construction project (Shahzad *et al.* 2014). The extent of offsite prefabrication in a construction project also determines whether a project is classed as non-volumetric offsite construction or volumetric offsite construction (Schoenborn 2012; Smith 2010; Gibb 1999). The non-volumetric offsite construction includes the use of processed materials and prefabricated building components (e.g. beams, columns, slabs, wall panels) and the volumetric offsite construction extends the inclusion of offsite components by constructing volumetric pods and modules offsite before installing them on site.

The main concept of offsite construction lies in the relocation of construction activities from site (in-situ) into a controlled environment offsite. Thus the central argument revolves around enabling these activities to be better planned and delivered similar to processes in manufacturing sector to achieve the intended outcomes (Barlow and Ozaki 2005). It has been argued that by delivering these construction activities in a controllable environment, safety, efficiency/productivity and quality could all be improved with less waste generated and therefore cost can be better controlled and less impact would be brought on the environment (Khalfan and Maqsood 2014; Krug *et al.* 2013; Azhar *et al.* 2011; Gibb 2001). The higher degree of standardisation and repetition in this controlled manufacturing environment has also been regarded as important factors to reduce dependency towards skilled trades by utilising semi-skilled or lower-skilled operatives (Nadim and Goulding 2009). These potential benefits from shifting construction activities to be conducted offsite has prompted the UK Government to consider offsite construction as the 'Modern Method of Construction' (MMC), particularly in the UK housing sector (Pan *et al.* 2008; Goodier and Gibb 2007; Gibb 1999).

In managing the offsite (manufacturing processes) and on site construction, the work breakdown structure (WBS) has been applied to model their processes. The WBS has been used to describe a hierarchical representation of the work to be executed by the project team, usually represented in a `top-down' orientation (Siami-Irdemoosa *et al.* 2015; Perdicoúlis 2013) and has been widely recognised as a powerful project management tool for better performance control (Hartmann *et al.* 2012; Wu *et al.* 2010; Chua and Godinot 2006). Thus its ability to define the scope and structure of the project and establishes the foundation for planning, budgeting, responsibility assignment, project control and information management has earned the WBS reputation as the most valuable tool for project management (Garcia-Fornieles *et al.* 2003). Whilst the relatively recent scholarly development [particularly in lean construction, [e.g. Koskela *et al.* (2002); Ballard (2000)] includes criticisms to the "classic project management" theory in which WBS serves as a fundamental concept to decompose projects, this research subscribes to a more reconciling few of Winch (2006) that the lean construction including its Last Planner system still consist of decomposition of the project through value stream mapping and process flow charting. Thus the difference is mainly in the subsequent procedures and not in the act of decomposition of the project itself.

From the manufacturing side, the works to be delivered mainly follow the product specifications. From the manufacturing perspective, the product design information have been considered an important factor in the interface between design and manufacturing process (Skander *et al.* 2007; Twigg 2002). Thus in manufacturing, the WBS typically shows the decomposition of products in such a way that the products at one level of WBS are the inputs to the next higher level (Wu *et al.* 2010). Following the input from a customer order, a WBS of functional components will be created to further determine the overall production schedule in which each of these functional components is mapped to its design engineering, production engineering, purchasing and manufacturing (Griess and Restrepo 2011) as presented in figure 1 below.

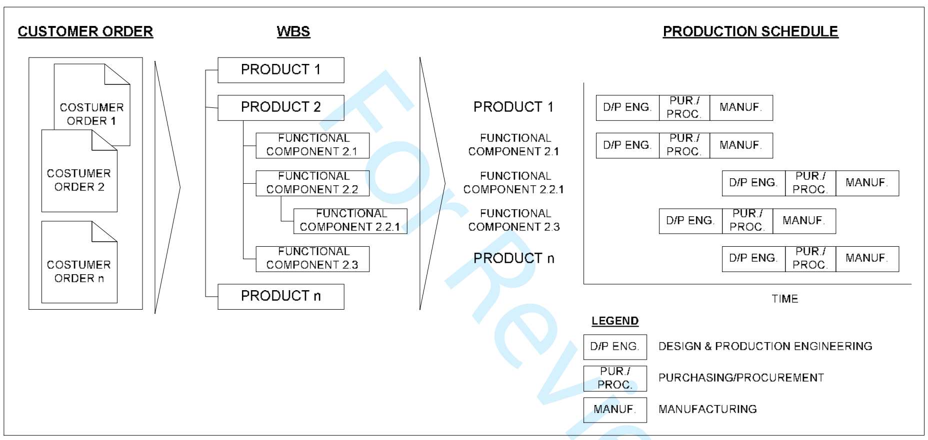

Figure 1. WBS in manufacturing (adapted from Griess and Restrepo 2011)

The WBS on the manufacturing side can be considered more oriented towards the products to be manufactured and typically resembles the product breakdown structure. Product breakdown structure itself has been defined as a hierarchical representation of the outcomes of a project, which may be physical products and/or services permitting an aggregation-detailing of the product (Perdicoúlis 2013). This style of upper stream breakdown is also considered within the scope the project management methodology, which has been regarded a key methodology in the manufacturing sector (Skander *et al.* 2007). From project management perspective, this type of WBS is considered as the deliverable-oriented WBS as opposed to the activity-oriented WBS (Rad 1999).

On the other hand, the WBS used in structuring construction activities in the construction industry is typically the activity-oriented WBS. Assuming the traditional construction procurement method as the most common choice in the construction industry (Masterman 2013), the design and specifications will inform the development of WBS. Following the development of the WBS, a construction schedule will be prepared based on an activity precedence networks that consider a project as a series of activities that can be related by links, which represent the planned order of work (Russel-Smith and Lepech 2012; Cole 1991). With the main emphasis on the project execution stage or construction stage, the WBS of a construction project can be considered the lower stream WBS and are typically prepared periodically for the scheduled works to be delivered using allocated resources and materials within the timeframe (Ahuja and Thiruvengadam 2004). Thus the main purpose of WBS in construction projects is decomposing the project into a hierarchical structure of construction activities and to determine the needed construction resources including labours, materials, equipment and administration to deliver the project and determine each activity's and eventually the whole project's time, cost, and quality (Hu and He 2014; Russel-Smith and Lepech 2012). These are presented in figure 2 below.

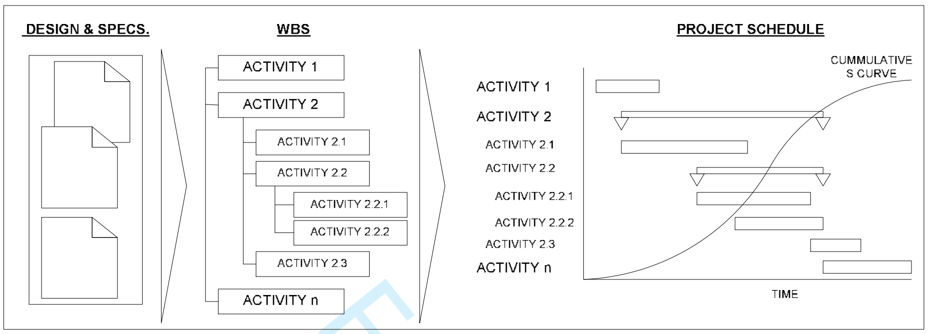

Figure 2. WBS in construction projects (adapted from Hu and He 2014; Russel-Smith and Lepech 2012)

Both PMBOK and PRINCE2 have suggested an intermediate phase to facilitated the transition from product oriented into activity oriented breakdown structure. The PMBOK recommends a decomposition components of the product phase (between the project scope definitions and the development of WBS) to subdivide the major project deliverables to support future project activities (PMI 2015) whilst the PRINCE2 advocates the creation of product flow diagram (between the development of product breakdown structure and the development of WBS) to identify and define the sequence of the components of the product to be developed that will naturally lead into consideration of the activities required (TSO 2009). Whilst it has been argued that a WBS should be a uniform, consistent, and logical method for dividing a project into small, manageable components for planning, estimating, and monitoring (Rad 1999), this paper does not intend to analyse the 'correctness' of the practices in the manufacturing and construction sectors but to highlight the differences in practice in those two sectors.

These differences in the manufacturing and construction practices in terms of WBS, however, have brought their own issues in the attempt to plan a smooth interface between the manufacturing and construction processes in offsite construction projects. Among various aspects identified as priorities in implementing offsite construction techniques, synchronising construction processes and activities with that of the manufacturing as well as better linking manufacturing schedules to actual construction processes have been considered high priority to be resolved (Arashpour *et al.* 2018; Arif *et al.* 2012). Incompatibilities in offsite construction projects that have been reported mainly stemming from the difficulties to synchronise the manufacturing activities that are repetitive in nature and in a highly controllable environment with the onsite construction tasks that are typically unique and carrying high uncertainty and variability in delivery (Salama *et al.* 2016; Harris and Ioannou 1998). Therefore, it can be argued that the synchronisation of the offsite manufacturing activities and onsite construction activities should be happen from the very early stage in offsite construction projects. As a WBS has been considered pivotal to the success of project management and planning (Siami-Irdemoosa *et al.* 2015), the synchronisation in this research is attempted at the development of WBS stage. The challenges remain at this stage as the conflicts between types of WBS used, particularly between the product oriented and activity oriented have been reported and acknowledged as an issue in the last two decades (NASA 2015; Godinot 2003; Christensen and Thayer 2001).

Given the differences in focus and hence differences in practices between the offsite manufacturing and onsite construction identified in the ongoing discussion, the synchronisation was not attempted to reduce either of them but to integrate. In looking for a suitable integration method, a tool known as WBS-matrix emerges as the potential solution to provide a systematic breakdown of the project into smaller components by recognising both product and activity views of the project (Chua and Godinot 2006; Godinot 2003). The basic concepts of WBS-matrix were first proposed by Bachy and Hameri (1997) in manufacturing production domain making clear distinction between product breakdown structure (PBS) and assembly/activity breakdown structure (ABS) before crossing them to form a matrix to subsequently determine distinctive work packages. Thus by simultaneously presenting and crossing these two breakdown structures (the information on the description of the intended product by specifying its main components and the information on activities and sub-activities to be performed), the resulting WBS-matrix clearly defines and support visualisation of the distinct work packages to be communicated to all project stakeholders. This reconfiguration of activities and product details allows the grouping together relevant product components or sub-activities that may not be necessarily displayed next to each other in either PBS or ABS. Whilst carrying potentials to bring together both product oriented and activities oriented work breakdown structure, however, the implementation of WBS-matrix can be considered limited in sectors such as building (Chua and Godinot 2006; Godinot 2003). Current literature reported WBS-matrix implementation in engineering projects (Yeh *et al*. 2017) as well as in designing modularisation in offsite projects (Isaac *et al*. 2014) but none so far reporting synchronisation of activity breakdown structure and product breakdown structure in offsite construction projects. Thus the main contribution of this paper includes expanding the current body of knowledge in the development of the WBS-matrix for offsite construction building projects signifying a step forward in resolving to the need for synchronisation in offsite construction projects.

Research Methodology

Research methodology should clearly explain the philosophical underpinning followed by the justification of the research design that includes its sampling, data collection procedure, data analysis method and demonstration of the research finding's credibility (Sutrisna and Setiawan 2016; Creswell 2003). This research is influenced by the critical realist paradigm, recognising that human beings can have access to reality albeit limited as well as accepting the co-existence of both objective and socially-constructed reality (Sutrisna and Barrett 2007; Lomborg and Kirkevold 2003). The ontological and epistemological stance of this research accepts the WBS as both an objective tool in delivering and managing offsite construction projects as well as a social system of how the project scope is recognised and accepted by its stakeholders to work together and interact with one another to complete the project. This stance has resulted in the broader consideration of WBS in this research not only as a project management tool but also as a representation of the stakeholder's background and mind-sets in articulating their roles in the project and interfacing with other stakeholders. This was found important in better understanding the reasons behind selecting a particular type of WBS in their project. This has also influenced the selection of the data collection method in the research that was aimed to compile objective evidence through archival study of cases and allow the researcher to develop an interpretation of "what happened" in the studied cases without being influenced by the project stakeholders' opinions and views.

In order to contextualise the use of WBS in offsite construction projects, case study has been selected as the research approach in this research to evaluate the current practices and formulating the way forward. Both physical and social dimensions of a phenomenon have been acknowledged to occur in specific contexts (Yin 2014; Robson 2011) and case study approach captures them as an empirical inquiry that investigates phenomena within their natural context and setting (Yin 2014). The research approach selected in a research is typically determined by the researcher's ontological and epistemological stance as well as the nature of the research problem itself (Sutrisna, 2009; Gill and Johnson, 1997). Thus, to understand the current practices in implementing activity based and product based WBS in offsite construction projects, it is considered necessary to investigate contextualised by case study approach, i.e. within the real world setting of such projects. Two cases, one in the Western Australia and one in England have been selected for this purpose. These two cases were selected due to their recent completion that represents the most contemporary practices in offsite construction projects with relatively high level of research attention towards the offsite construction technique in both countries. Both selected cases are primary/secondary educational projects of similar size and complexity suitable for comparison purposes. The selection of the two cases was intended to highlight the different use of product based and activities based WBS in these two offsite construction projects. The profiles of the cases are provided in table 1.

Table 1. The case study profiles

Profile	**Case 1**	**Case 2**
Project type/scope	New build 2 storey educational building	New build 2 storey educational buildings
Floor Area	1,980 m^2	2,250 m^2
Offsite elements	47 volumetric units	56 volumetric units
Project location	Western Australia	England
Project duration	10 months	13 months
Project budget	£ 3.286 M*	£ 4.023 M

*exchange rate used £1 = AU$ 1.613

As the main focus was on the implementation of WBS in these two projects, the data collection in this research was conducted through archival study, supplemented by clarification discussions with the offsite construction providers whenever found necessary. This is mainly due to the fact that the offsite construction providers in the two cases performed the role of the offsite manufacturers as well as the main construction contractor and offered a complete package solution for the projects. Archival study is therefore considered suitable to provide evidence of the most current practices of WBS implementation in offsite construction projects. Thus, the importance of the archives themselves to this research has justified its application as a standalone method in this qualitative research [for further discussion on archival study as a standalone in qualitative research, please refer to Bowen (2009)].

In archival study, the archives are typically considered as potential sources of evidence of past events representing those events from the objectivist's point of view whilst from the subjectivist's perspective, the archives are treated as "the way" to socially contextualise and understand those events (Furner 2004). Therefore, the archival study is considered inline with the critical realist stance of this research that accepts both point of views and utilises both perspectives in studying the archives. The archival study was conducted by analysing project reports, technical drawings and specifications, correspondences between the client and the offsite construction providers as well as project costing and project schedule/programme. In interpreting meanings, it was found prudent to seek clarification of certain points with the offsite construction providers but only when needed allowing the development of a holistic understanding of the two projects from a neutral point of view. Due to the aim of this research, i.e. to evaluate the current implementation of WBS in offsite construction projects, findings were allowed to emerge naturally from the archival study of real-life projects rather than from its stakeholder's opinions. The informal discussions were held with the project manager, factory manager, construction manager and technical director of the offsite construction providers but only served for clarification purposes. It is anticipated that the further development of this research may involve formal interviews with (offsite) construction practitioners, mainly to formulate the way forward, but this will be beyond the scope of this article.

Findings and Discussion

Case Study 1

The WBS of case 1 is presented within the project programme/schedule in figures 3 and 4 respectively. Figure 3 captured the first page of the project programme/schedule to show the first five of the offsite manufacturing items (volumetric modules number 1 to 5) and figure 4 captures the third page of the programme/schedule to show the last manufacturing item (volumetric module number 47) and the construction activities.

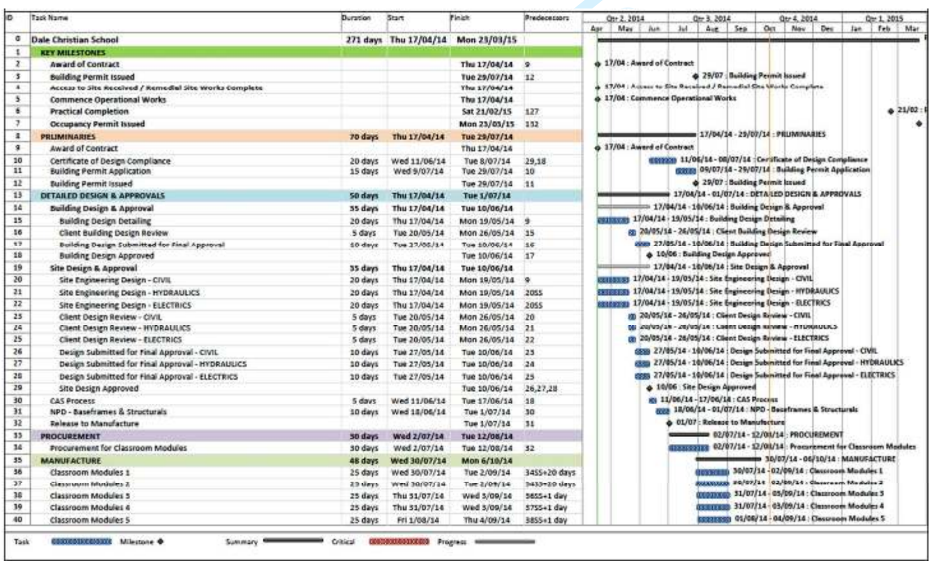

Figure 3. The first page of case 1 project programme/schedule.

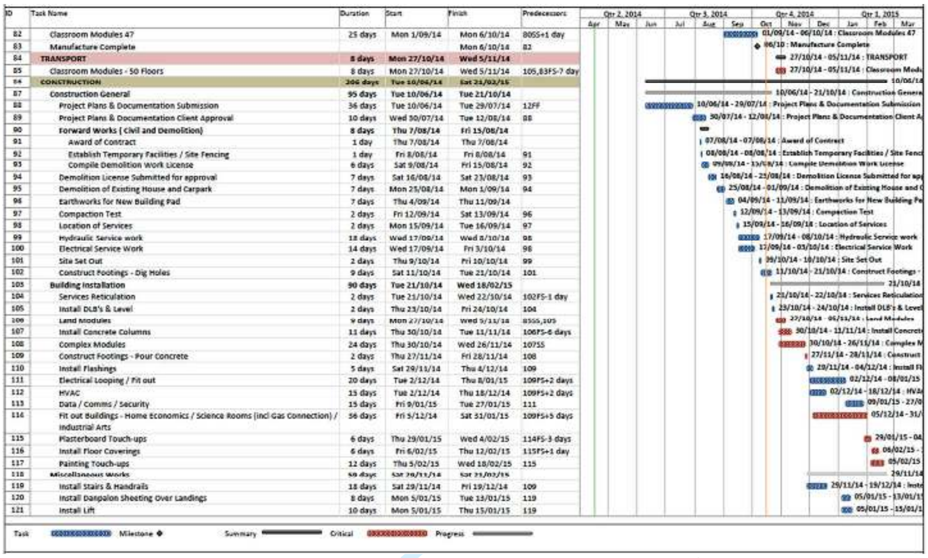

Figure 4. The third page of case 1 project programme/schedule.

The WBS of the programme/schedule in this project was developed mainly based on activities with the exceptions of the offsite manufacturing process of the volumetric modules (modules 1 to 47). The offsite manufacturing process was represented by the products (the volumetric modules), which were scheduled to be completed in 25 days each. This is one of the most common ways of representing the offsite manufacturing tasks in WBS of offsite construction projects. The offsite construction provider in this case clarified that it is not a common practice in the sector to breakdown further into activities/sub-activities within each volumetric module as the manufacturing process is different from the way onsite construction activities/sub-activities would be broken down. As many of the offsite tasks are typically sub-contracted, particularly for the labour, the most common way is to track down the milestone, i.e. requiring each volumetric module (which are all comparable in terms of complexity, size, materials and resource needs), to be completed within 25 days in this case. This has unveiled the views from the offsite construction provider that the modules are perceived as "manufactured products" and the role of the manufacturing sub-contractors as the suppliers of the products rather than as the constructors as it would typically be perceived in traditional onsite construction projects.

Whilst understandable and can be considered common practice from the manufacturing sector perspective, this practice is does not convey the same level of information to the construction side of the project. Thus, from the construction project management's point of view, the offsite manufacturing tasks appear to be a "black box" process simply represented by a single item in the WBS that merely describes the final product. The product oriented WBS represents the upper stream or earlier phase of the development of WBS that will typically transform into activities oriented WBS in the later stage to support the management of project's activities and project delivery (PMI 2015; TSO 2009; Rad 1999). Thus, this particular case study has provided evidence that this "black box" approach is a common approach in the construction industry and further discussion has pointed out that within the context of offsite construction projects, the product oriented WBS is needed mainly to manage the offsite manufacturing processes but the activities oriented version of the WBS should also be prepared to synchronise the entire project in a holistic manner. This synchronisation between manufacturing schedules to actual construction processes have been considered high priority in the further development of offsite construction to be resolved (Arif *et al.* 2012).

Case study 2

The WBS of case 2 is presented within the project programme/schedule in figures 5 and 6 respectively. Figure 5 captured the first page of the project programme/schedule to show the higher activity of the offsite manufacturing items (Factory Manufacture Period/Module Fabrication Summary) and figure 6 captures the second page of the programme/schedule to show the manufacturing tasks as well as the beginning of the construction tasks of the smaller building out of two buildings as examples of the manufacturing and construction tasks.

This project consists of a smaller nursery building and the main secondary classroom building. The offsite construction portion is a part of a larger project that also includes extensive external works as well as the onsite construction of a school hall and other facilities. For the comparison purpose between the two projects in this research, only the construction of the smaller nursery building and the main secondary classroom buildings are included in the analysis as they are the ones that were built with offsite construction methodology. For example, the project value described here (refer to table 1) excludes other construction works that were beyond the scope of the offsite construction provider in this case.

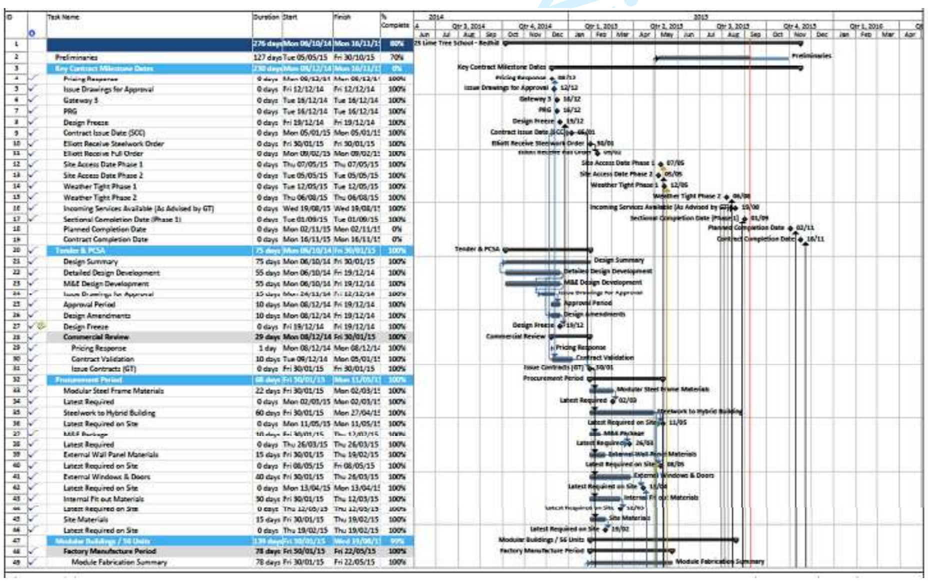

Figure 5. The first page of case 2 project programme/schedule.

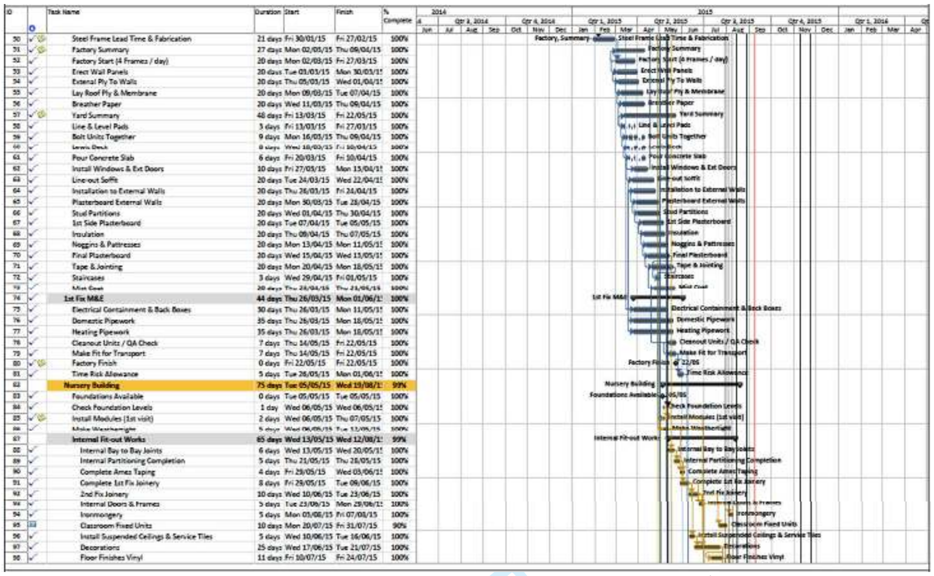

Figure 6. The second page of case 2 project programme/schedule.

Underpinned by the findings in case 1 that activities based WBS is also needed in an offsite construction project, particularly from its project management point of view, attention was now focused on case 2. The WBS of the programme/schedule in this project was developed mainly based on activities including for the manufacturing tasks. Different from the approach applied in case 1, the development of the WBS in case 2 follows the style of the onsite construction WBS. This has unveiled the opposing view of the offsite construction provider in this case that the modules are perceived as a set of activities to be performed by their subcontractors and/or their internal team. The initial expectation was that case 2 project will demonstrate a more "construction-friendly" approach compared to case 1 as the WBS used in case 2 was based on activity which is more inline with WBS in its onsite counter parts. However, it was evident that even in a WBS that was developed to represent activities, there is still a need for information typically contained in the product breakdown. An example would be task number 72, staircases. As the steel stairs in case 2 were supplied by a specialised manufacturer, they have to be connected to the relevant steel frames of the volumetric modules. Therefore, in this case, that particular item refers to a task to install the steel stair and finalising the staircase part of the relevant volumetric modules. The WBS, however, does not provide the information regarding which volumetric module this task should apply at which point in time. Information such as this is would have been typically provided by the product breakdown structure or product oriented WBS. This example has demonstrated the fact that even though the WBS of the manufacturing portion in an offsite construction project has been designed to be activity oriented WBS, there is still a need to have the product oriented WBS.

This matter has also been recognised in the general project management domain. PRINCE2 methodology for example, advocated that one of the functions of product breakdown structure is to identify external products (already exist or to be created) that are required to complete the products within the scope of the project (TSO 2009). The product breakdown structure has been regarded particularly useful to uniquely identifying all components that makes the end product as well as providing common reference for explicitly associating the characteristics of the product and/or components that make up the final product (Lamers 2002). Underpinned by the literature as well as by the case study in this research, it can be argued that whilst activities breakdown structure or activity based WBS is needed in offsite construction projects, the product breakdown structure containing the necessary information to manage projects, is also needed in offsite construction projects if a holistic project management is to be implemented in such projects. Hence, this research attempts to bring together and simultaneously display information in both product-oriented and activities-oriented WBS of offsite construction projects using a technique known as the WBS-matrix.

Development of WBS-matrix

The development of the WBS-matrix in this research follows the procedures recommended by Chua and Godinot (2006), i.e. by crossing the product-oriented breakdown structure (product-oriented WBS) and the activities oriented breakdown structure (activities oriented WBS). One of the most important matters was the determination of the level of details that should be included in the matrix. From the manufacturing perspective, the product-oriented breakdown structure should be based on the functional components of the product (Griess and Restrepo 2011). Using the information from a typical volumetric unit in both projects, the main components of a typical volumetric unit to be included are the steel chassis (volumetric frame), external walls, roof/ceiling, internal walls, floors and mechanical/electrical/plumbing (MEP). The level of finishing and completeness of these components in a volumetric module differs from one offsite construction projects to another but these main components will most likely be constructed before they are transported to their onsite positions to benefit from the offsite technique. From the construction perspectives, the activities-oriented breakdown structure should include the main activities to complete the project (Russel-Smith and Lepech 2012). Thus, in this case, the intention here is to construct a volumetric module ready to be transported to site. Using the WBS items from case 2 (refer to figures 5 and 6) which is an activity-based WBS to represent the recommended level of breakdown for typical offsite activities and therefore used as the basis for further development, the WBS-matrix for a typical offsite construction project can be developed by crossing the product-oriented and activities oriented WBS as presented in figure 7 below.

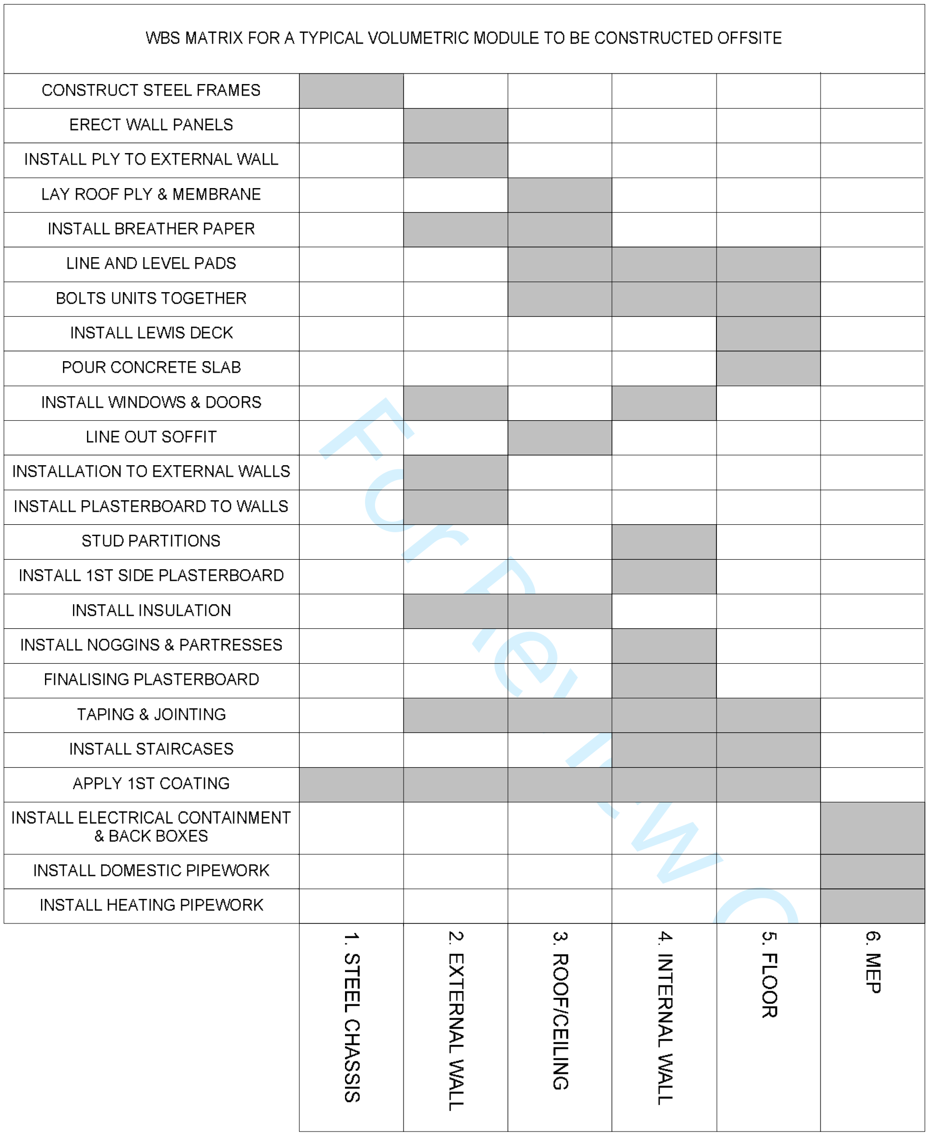

Figure 7. A proposed WBS-matrix for typical offsite construction projects

Figure 7 above is not intended to be a "one size fits all" WBS-matrix for all kind of offsite building construction projects but more of an example how the WBS-matrix for an offsite construction project can be developed. It is now made clear in the WBS-matrix which activities contributing to which product and/or functional components of a product. For example, it is now made clear that an activity known as "Install Windows and Doors" occurred in the "External Wall" and "Internal Wall" components of that volumetric module. It should be noted, however, the WBS-matrix shown above represents activities and functional components of only one volumetric module. Following the same principle, this WBS-matrix can be expanded to include all volumetric modules in an offsite construction project.

As previously mentioned, one of the main difficulties reported are mainly due to the repetitive nature of manufacturing for offsite construction operations (Salama *et al.* 2016). As evidenced in case 1 of this study, the product-oriented WBS carries this repetition of the volumetric modules whilst in case 2 there is literally no information regarding the volumetric modules in its activities-oriented WBS. So, continuing previous example of "Install Windows and Doors" activity for instance. It is now made clear that this activity occurred in constructing both "internal Wall" and "External Wall" components of a volumetric unit. However, this matrix still does not contain information of when the "Install Windows and Doors" activity is to be performed and for which modular unit it should be performed. In order to deal with these, time dimension can be added to the WBS matrix as its third dimension. In order to visualise this, the functional product breakdown can be represented by the x axis, the activities breakdown by the y axis and time by the z axis. This can be illustrated by using the first three activities of constructing one volumetric module from the WBS-matrix as presented in figure 8 below.

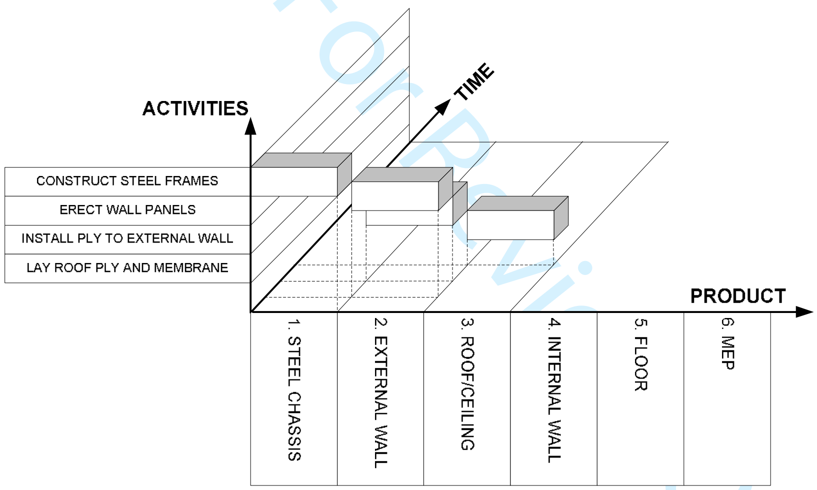

Figure 8. WBS-matrix with added time dimension for one volumetric module

By adding the third dimension to the WBS-matrix as presented in the figure 8 above, the repetition of the activities and functional component representing the volumetric modules can be presented along the time axis and relationship between them can be illustrated. The pattern of the repetition will depend on other factors such as the number and availability of the factory floor, machineries/tools, materials and resources. After all, time and duration are the main reference points of any scheduling but even more so in manufacturing scheduling and decision-making (Framinan *et al.* 2014). Taking the example in figure 8 above, other volumetric modules can be added so for example how many times "erecting wall panel" activities have to be performed to construct the "external wall" component for which volumetric module can be presented (for multiple volumetric modules). Whilst it maybe more complex to visualise, if this repetition pattern can be modelled and presented in the extended version of the WBS-matrix, a more holistic modelling of the process can be provided to further support and inform decision making in managing offsite construction projects. The "WBS-matrix" and "WBS-matrix with added time dimensions" for offsite construction projects reported here can be used to supplement the more traditional project programme/schedule to fully appreciate the manufacturing process of the offsite components in the project. This can be considered a further improvement from the current practice of including them in the project programme/schedule as a product (case 1) or list of activities (case 2) alone. The overall project programming/scheduling of an offsite construction project can also be presented in the WBS-matrix format to upgrade them, particularly with added time dimension to incorporate both product and activity WBS. However, this level of complexity may make it much harder for users to visualise. A possible tool that can be used to minimise this visualisation issue would be using 3-D visualisation tools and this area needs further research on the capabilities of software applications to model volumetric objects and do 4-D simulation. An example of this possibility is presented in figure 9, which was developed using Autodesk Revit 2017.

Formatted: Font: Garamond

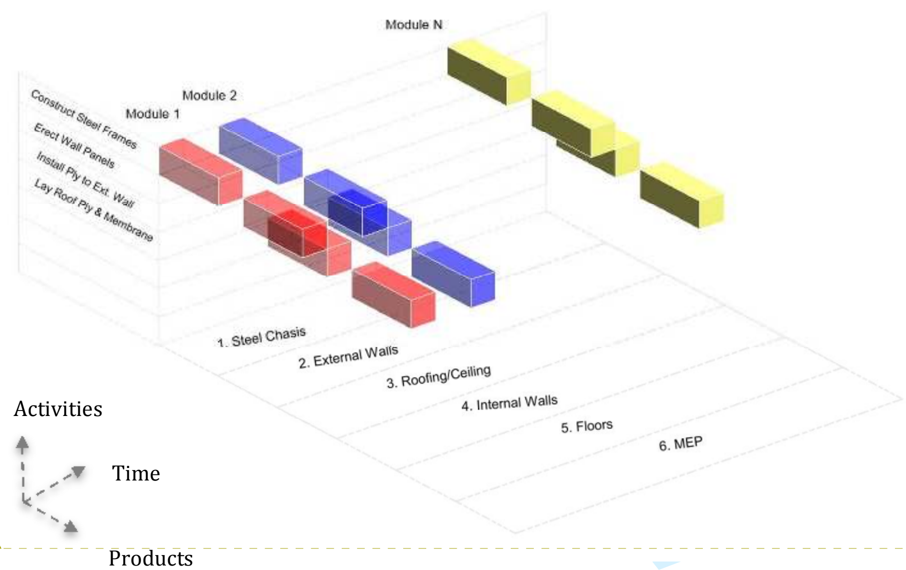

Figure 9. WBS-matrix with added time dimension in a 3-D visualisation tool.

Each volumetric object is considered as a work package and can be modelled as a 'mass object' with three instants properties: 'Product Name', 'Activity Name' and 'Module Name'. By presenting the WBS-matrix in Autodesk Revit, the construction sequence, different elements of the volumetric module and time dimension can be presented in 3D and can be clearly visualised. For project stakeholders with no access to specific software applications, such as Naviswork, the construction stimulation can be converted to more common data formats (for example, Windows AVI). This will facilitate more clarity in sharing the planned construction procedure. This higher degree of visualisation also supports progress monitoring by making it more transparent compared to Gantt charts for instance. However, this area of investigation will be in the subsequent phase of this research project and is outside the scope of this paper.

Conclusion

Offsite construction can be considered a viable methodology for delivering AEC projects if (and only if), processes are fully understood by all parties. Managing construction projects (including offsite) through WBS is an acknowledged approach for product delivery. The WBS of both the offsite and onsite construction products/activities therefore need to be fully understood from the outset in order to purposefully deliver synchronisation. This work was promulgated on the reported mismatch between the construction WBS and manufacturing WBS; the remit of which was to investigate this and determine viable solutions and concomitant integration strategies. The origins of the differences between the product-oriented WBS (originating from the manufacturing side), and the activities-oriented WBS (originating in the construction side) provide fertile grounds for discussion and opportunities for improvement. From this, a WBS-matrix for offsite construction projects was developed and presented, cognisant of the need to combine the two types of WBS into a more integrated solution for offsite construction projects.

Whilst it is acknowledged that the findings and proposed WBS-matrix presented here is only developed for one volumetric module, there are significant opportunities for exploring further developments, including incorporating multiple volumetric modules in an extended WBS-matrix. An extended WBS-matrix for offsite construction projects represents a further subsequent phase of this research, which is for now beyond the scope of this paper. However, the development of the WBS-matrix for offsite construction presented here signifies a major step forward in recognising the need for synchronisation – albeit representing the first phase. Given this, the methodology presented can be used as the basis for developing a WBS-matrix for different types of offsite construction projects (depending on the unique needs of a particular project). Further research will need to appreciate the interconnectivity of multiple volumetric modules, including exploring other types of breakdown structure such as organisational breakdown structure (OBS), resources breakdown structure (ReBS) and/or risk breakdown structure (RiBS). Peripheral and contextual issues will also need to be analysed, including dimensional or geospatial nuances, locational or unique functional product-parameters, factory floor/ machinery characteristics etc. Greater understanding of these issues is important for developing improved richness and understanding, particularly evidential veracity on the value proposition stream. It is hoped that this will in turn support the wider uptake and implementation of offsite construction.

Acknowledgement
The authors would like to acknowledge the support from Ausco Modular (Australia) and Elliot (UK) in providing the case study datasets for this work.

References

Ahuja, V. and Thiruvengadam, V. (2004), 'Project scheduling and monitoring: current research status', *Construction Innovation*, **4**(1), pp.19-31.

Arashpour, M., Wakefield, R., Abbasi, B., Arashpour, M. and Hosseini, R. (2018) 'Optimal process integration architectures in off-site construction: Theorizing the use of multi-skilled resources', *Architectural Engineering and Design Management*, **14**(1-2), pp. 46-59,

Arif, M., Bendi, D., Sawhney, A. and Iyer, K.C. (2012), 'State of offsite construction in India-Drivers and barriers, *Journal of Physics: Conference Series*, **364**, pp. 1-8.

Azhar, S., Carlton, W.A., Olsen, D. and Ahmad, I. (2011), 'Building information modeling for sustainable design and LEED® rating analysis', *Automation in construction*, **20**(2), pp.217-224.

Barlow, J. and Ozaki, R. (2005), 'Building mass customised housing through innovation in the production system: lessons from Japan', *Environment and Planning A*, **37**(1), pp.9-20.

Ballard, H.G. (2000) *The last planner system of production control*, Unpublished PhD Thesis, University of Birmingham, Birmingham, UK.

Blismas, N. and Wakefield, R. (2009), 'Drivers, constraints and the future of offsite manufacture in Australia', *Construction innovation*, **9**(1), pp.72-83.

Bowen, G. A. (2009), 'Document Analysis as a Qualitative Research Method', *Qualitative Research Journal,* **9**(2), pp.27-40.

Christensen, M. J., and Thayer, R. H. (2001), 'The work breakdown structure', *In:* The project manager's guide to software engineering's best practices, IEEE Computer Society, Los Alamitos, CA.

Chua, D. K. H. and Godinot, M. (2006), 'Use of a WBS Matrix to Improve Interface Management in Projects', *Journal of Construction Engineering Management*, **132**(1), pp. 67-79

Cole L. (1991), 'Construction Scheduling: Principles, Practices, and Six Case Studies', *Journal of Construction Engineering Management*, **117**(4), pp. 579-588.

Creswell, J.W. (2003), *Research design: Qualitative, quantitative, and mixed methods approaches*, 2nd ed., Sage Publication, Thousand Oaks, CA.

Framinan, J. M., Leisten, R. and García, R. R. (2014), *Manufacturing Scheduling Systems: An Integrated View on Models, Methods and Tools*, Springer-Verlag, London.

Furner, J. (2004), 'Conceptual analysis: A method for understanding information as evidence, and evidence as information', *Archival Science*, **4**(3), pp.233-265.

Garcia -Fornieles, J.M., Fan, I.S., Perez, A., Wainwright, C. and Sehdev, K. (2003), 'A work breakdown structure that integrates different views in aircraft modification projects', *Concurrent Engineering*, **11**(1), pp.47-54.

Gibb, A. G. F. (1999), *Offsite Fabrication: Prefabrication, Pre-assembly and Modularisation*, Whittles Publishing, Caithness, UK.

Gibb, A.G. (2001), 'Standardization and pre-assembly-distinguishing myth from reality using case study research', *Construction Management & Economics*, **19**(3), pp.307-315.

Gill, J. and Johnson, P. (2010). *Research methods for managers*, 4th ed., Sage Publication, Thousand Oaks, CA.

Godinot, M. (2003), *The work breakdown structure matrix: A tool to improve interface management*, Unpublished Master of Engineering Thesis, Department of Civil Engineering National University of Singapore.

Goodier, C. and Gibb, A. (2007), 'Future opportunities for offsite in the UK', *Construction Management and Economics*, **25**(6), pp.585-595.

Goulding, J.S., Pour Rahimian, F., Arif, M. and Sharp, M.D. (2015), 'New offsite production and business models in construction: priorities for the future research agenda', *Architectural Engineering and Design Management*, **11**(3), pp.163-184.

Gries, B. and Restrepo, J. (2011), 'KPI Measurement in Engineering Design – A Case Study', *International Conference on Engineering Design*, ICED11, 15 - 18 August 2011, Technical University of Denmark, Copenhagen, Denmark.

Harris, R. and Ioannou, P. (1998), 'Scheduling Projects with Repeating Activities', *Journal of Construction Engineering Management*, 124(4), pp. 269-278.

Hartmann, T., van Meerveld, H., Vossebeld, N. and Adriaanse, A. (2012), 'Aligning building information model tools and construction management methods', *Automation in Construction*, **22**(2012), pp. 605–613.

Hu, W. and He, X. (2014), 'An innovative time-cost-quality tradeoff modeling of building construction project based on resource allocation', The Scientific World Journal, 2014, http://dx.doi.org/10.1155/2014/673248.

Isaac, S., Bock, T. and Stoliar, Y. (2014), 'A new approach to building design

modularization', *Procedia Engineering*, **85**(2014), pp. 274 – 282.
Jonsson, P., Rudberg, M. and Holmberg, S. (2013), 'Centralised supply chain planning at IKEA', *Supply Chain Management: An International Journal*, **18**(3), pp.337-350.
Kale, S. and Arditi, D. (2006), 'Diffusion of ISO 9000 certification in the precast concrete industry', *Construction Management and Economics*, **24**(5), pp.485-495.
Kamar, A.M., Hamid, Z.A. and Azman, N.A. (2011), 'Industrialized building system (IBS): Revisiting issues of definition and classification', *International journal of emerging sciences*, **1**(2), p.120-132.
Khalfan, M. M. A. and Maqsood, T. (2014), 'Current State of Off-Site Manufacturing in Australian and Chinese Residential Construction', *Journal of Construction Engineering*, http://dx.doi.org/10.1155/2014/164863.
Koskela, L., Huovila, P. and Leinonen, J. (2002), 'Design management in building construction: from theory to practice', *Journal of construction research*, **3**(01), pp.1-16.
Lamers, M. (2002), 'Do you manage a project or what? A reply to "Do you manage work, deliverables or resources", *International Journal of Project Management*, April 2000', *International Journal of project Management*, **20**(2002), pp. 325-329.
Lomborg, K. and Kirkevold, M. (2003), 'Truth and validity in grounded theory – a reconsidered realist interpretation of the criteria: fit, work, relevance and modifiability', *Nursing Philosophy*, **4**(3), pp. 189-200.
Masterman, J. W. E. (2013), *An introduction to building procurement systems*, 2nd *ed.*, Taylor & Francis, London.
Nadim, W. and Goulding, J.S. (2009), 'Offsite production in the UK: The construction industry and academia', *Architectural Engineering and Design Management*, **5**(3), pp.136-152.
NASA (2015), *NASA cost estimating handbook*, 4th ed., National Aeronautics and Space Administration, Washington D. C., URL: https://www.nasa.gov/pdf/263676main_2008-NASA-Cost-Handbook-FINAL_v6.pdf, viewed: 01/09/2017.
Pan, W. and Goodier, C. (2012), 'House-building business models and off-site construction take-up', *Journal of Architectural Engineering*, **18**(2), pp. 84–93.
Pan, W., Gibb, A.G. and Dainty, A.R. (2008), 'Leading UK housebuilders' utilization of offsite construction methods', *Building Research & Information*, **36**(1), pp.56-67.
Perdicoúlis, A. (2013), 'Hierarchical breakdown structures', *Systems Planner*, **23**, pp. 1 -7.
PMI (2015), *A Guide to the Project Management Body of Knowledge (PMBOK Guide)*, 5th ed., Project Management Institute, Newtown Square, PA.
Rad, P.F. (1999), 'Deliverable -oriented work breakdown structure, *AACE International Transactions: Morgantown*, pp. CSC 021- CSC. 026.
Ramaji, I. J. and Memari, A. M. (2018), 'Extending the current model view definition standards to support multi-storey modular building projects', *Architectural Engineering and Design Management*, **14**(1-2), pp. 158-176.
Richard, R. B. (2005), 'Industrialised building systems: reproduction before automation and robotics', *Automation in Construction*, **14**(2005), pp. 442 – 451.
Robson, C. (2011), *Real world research: A resource for users of social research methods in applied settings*, 4th ed., Wiley-Blackwell, Hoboken, NJ.
Russell-Smith, S. and Lepech, M. (2012), 'Activity -based methodology for life cycle assessment of building construction', In: *CIBSE ASHRAE Technical Symposium*, Imperial College, London UK, 18-19 April 2012, pp. 1-13.
Salama, T., Salah, A. and Moselhi, O. (2016), 'Alternative Scheduling and Planning Processes for Hybrid Offsite Construction', *Proceeding of the 33rd International Symposium on Automation and Robotics in Construction (ISARC 2016*), 18-21 July 2016, Auburn, Alabama, USA, International Association for Automation and Robotics

in Construction (IAARC), pp. 146-153.
Schoenborn, J., 2012. *A case study approach to identifying the constraints and barriers to design innovation for modular construction*, Doctoral dissertation, Virginia Polytechnic Institute and State University, Blacksburg, VA.
Shahzad, W.M, Mbachu, J. and Domingo, N. (2014), 'Prefab content versus cost and time savings in construction projects: A regression analysis', *Proceedings of the 4th New Zealand Built Environment Research Symposium (NZBERS)*, Auckland, New Zealand. 14 November.
Siami-Irdemoosa, E. Dindarloo, S. R. and Sharifzadeh, M. (2015), 'Work breakdown structure (WBS) development for underground construction', *Automation in Construction*, **58**(2015), pp. 85–94.
Skander, A., Roucoules, L. and Meyer, J.S.K. (2008), 'Design and manufacturing interface modelling for manufacturing processes selection and knowledge synthesis in design', *The International Journal of Advanced Manufacturing Technology*, **37**(5-6), pp.443-454.
Smith, R. E. (2010), *Prefab Architecture: A Guide to Modular Design and Construction*, John Wiley & Sons, Hobboken, NJ.
Steinhardt, D. A and Manley, K. (2016), 'Adoption of prefabricated housing–the role of country context', *Sustainable Cities and Society,* **22**(2016), pp. 126–135.
Sutrisna, M. (2009), 'Research Methodology in Doctoral Research: Understanding the Meaning of Conducting Qualitative Research', *In:* Ross, A. (Ed.), *ARCOM Doctoral Workshop*, Liverpool, 12 May 2009, pp. 48-57.
Sutrisna, M. and Barrett, P. (2007), 'Applying rich picture diagrams to model case studies of construction projects', *Engineering, Construction and Architectural Management*, **14**(2), pp. 164-179.
Sutrisna, M. and Setiawan, W. (2016), 'The Application of Grounded Theory Methodology in Built Environment Research', *In:* Ahmed, V., Opoku, A., and Aziz, Z. (Eds.), *Research Methodology in the Built Environment: A Selection of Case Studies*, Taylor and Francis, Oxford.
Sutrisna, M., Lofthouse, B. and Goulding, J. (2017), 'Exploring the Potential of Offsite Construction to Alleviate Constraints to House Building in Western Australia', *Proceeding of the International Research Conference: Shaping Tomorrow's Built Environment in conjunction with CIB*, Salford, 11-12 September 2017, pp. 896-907.
TSO (2009), *Managing Successful Project with PRINCE2®*, 2009 ed., The Stationary Office, London.
Twigg, D. (2002), 'Managing the design/manufacturing interface across firms', Integrated manufacturing systems, 13(4), pp.212-221.
Winch, G.M. (2006), 'Towards a theory of construction as production by projects', *Building research & information*, **34**(2), pp.154-163.
Winch, G. M. and Kelsey, J. (2005), 'What do construction project planners do?', *International Journal of Project Management*, **23**(2005), pp. 141–149.
Wu, Z., Schmidt, L. P. and Wigstrom, W. S. (2010), 'Product Development Workflow Management Based on Work Breakdown Structure', *In:* Johnson, A. and Miller, J. (eds.), *Proceedings of the 2010 Industrial Engineering Research Conference* , 6 May 2014,
Yeh, H.H., Hsieh, T.Y. and Chen, J.H., 2017. Managing Complex Engineering Interfaces of Urban Mass Rapid Transit Projects. *Journal of Construction Engineering and Management*, **143**(6), p.05017001.
Yin, R. K. (2014), *Case Study Research: Design and Methods*, 5th ed., Sage Publication. Thousand Oaks, CA.