A BIM-based approach for DfMA in building construction: framework and first results on an Italian case study

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A BIM-based approach for DfMA in building construction: framework and first results on an Italian case study

BIM (Building Information Modelling) adoption is growing rapidly across Europe (Becerik-Gerber & Kensek, 2009; Tulubas Gokuc & Arditi, 2017). Since BIM alone would hardly meet the Construction 2025 targets, the Government Strategy aims at enabling a range of wider initiatives – including Modern Methods of Constructions (MMC). Design for Manufacturing and Assembly (DfMA) is considered one of these advanced forms of construction (Antwi-Afari, Li, Pärn, & Edwards, 2018; Becerik-Gerber & Kensek, 2009; Goulding, Pour Rahimian, Arif, & Sharp, 2015; Thompson, Juel Jespersen, & Kjærgaard, 2018; Wong & Fan, 2013). This research looks at DfMA applications in UK and Singapore (Antwi-Afari et al., 2018; W. Zhang, Lee, Jaillon, & Poon, 2018), and attempts to build upon a structured process. Two adopted frameworks are presented: the RIBA Plan of Work 2013 (adapted for DfMA) and the BCA BIM for DfMA (Olawale & Sun, 2010; Sun & Meng, 2009). Both have been used to link DfMA downstream activities (procurement, fabrication, transport, installation) to upstream activities (brief, option appraisal, concept design), reaching comparisons and integrations of these processes with traditional design process adopted in Italy for public developments. Starting from a critical analysis of existing frameworks, a revised DfMA workflow for Italian AEC sector is developed. A case study (a kindergarten in Italy) is analysed in its DfMA peculiarities, focusing on one sub-system manufactured offsite (bathroom pods), using data derived from manufacturers and designers. The developed case study has been used to test the proposed flow of information requirements and to identify shortfalls or improvements in current processes. The proposed framework is integrated and compared with existing design process acknowledged by the Italian Government for public buildings. The results confirmed the need for precisely structured procedures in delivering an offsite-oriented project. The framework presented guided the production, collection and organisation of data at each stage to integrate DfMA solutions into the project, while the proposed process confirmed its applicability. This research opens to scenarios of gradual implementation of DfMA-related processes, including different building sub-systems to enhance the framework and process content with additional lessons learnt.

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Keywords: prefabrication; design for manufacturing and assembly; off-site construction, process matrix.

Glossary

AEC: Architecture, Engineering and Construction

BCA: Building and Construction Authority of Singapore

BEP: BIM Execution Plan

BIM: Building Information Model/Modelling

CNC: Computer Numerical Control

DfMA: Design for Manufacturing and Assembly

*DIP: Documento di Indirizzo alla Progettazione

EIR: Employer Information Requirements

LPS: Last Planner System

MEP: Mechanical, Electrical and Plumbing

MMC: Modern Methods of Construction

QA: Quality Assessment

*QE: Quadro Esigenziale

RIBA: Royal Institute of British Architect

SC: Supply Chain

VDC: Virtual Design Construction

*Italian regulation documents, under approval at the time of the research.

Introduction and research background

The adoption of BIM (Building Information Modelling) is growing rapidly across Europe (Alwan, Jones, & Holgate, 2017; Antwi-Afari et al., 2018; Tulubas Gokuc & Arditi, 2017; Wong & Fan, 2013). The UK Government believes that BIM will help in delivering projects for lower cost, shorter time, with fewer carbon emissions and a better trade balance for construction projects (HM Cabinet Office, 2011; HM Government, 2013). Players researching in BIM-manufacturing integration are growing in numbers (Alwisy, Bu Hamdan, Barkokebas, Bouferguene, & Al-Hussein, 2018; Babič, Podbreznik, & Rebolj, 2010; Barlish & Sullivan, 2012; Smith, 2014), supported by initiatives of the Government (Bytes and Mortar in UK, Construction Sector Deal) (UK Department for Business Energy & Industrial Strategy, 2018a)(UK Department for Business Energy & Industrial Strategy, 2018b), by institutions (i.e. Institution of Civil Engineers) (ICE, ICG, & Mott MacDonald, 2018) and by the market demand (McGraw-Hill Construction, 2012). Consequently, the AEC sector has to face some challenges related to this shift (i.e. industry fragmentation, transparency among disciplines, regulation, contracts, design processes, onsite execution, technology and digital integration, workforce skills, etc.) – as reported by McKinsey and others. Also, policies established by the EU 2050 Roadmap (European Climate Foundation, 2010; European Commission, 2012), having as objective a more climate-oriented and less energy-consuming European economy, demand high-level performances from the building sector. In February 2017, McKinsey performed a research on labour productivity in the construction sector (defined as the value added by construction workers) and its growth over time. It showed that globally, construction has averaged 1% growth (period 2015-2017), compared with a growth of 2.8% for the total world economy and 3.6% for manufacturing (McKinsey Global Institute, 2017). The research also proved that many construction projects suffer from overruns in cost and time. One way to reach higher labour productivity could be through shorter and more reliable schedules, hence the focus on new design and delivery processes as well as on new digital tools (Olawale & Sun, 2010; Sun & Meng, 2009).

In the UK, since BIM alone would hardly meet the Construction 2025 targets (HM Government, 2013), the Government Strategy was intended to enable a range of wider initiatives - including Modern Methods of Constructions (MMC) (HM Treasury, 2017). Design for Manufacturing and Assembly (DfMA) is considered as one of these advanced forms of construction, and the Government (like many private Clients) demands a solid and low-risk development platform to invest in DfMA adoption. UK 2017 Autumn Budget states that this consistent demand is possible (HM Treasury, 2017), starting from paths already undertaken by its Ministry of Justice, Education and Skills Funding Agency, Crossrail and Highways England. To meet these targets, in May 2017 the Industrial Strategy Challenge Fund was published as part of the UK government's £4.7 billion investment in R&D over 4 years. In May 2018, the UK Department for Business, Energy & Industrial Strategy (DBEIS) partnered with industry (CITB: Construction Industry Training Board) to launch "Bytes and Mortar". A Construction Sector Deal worth £420 million to transform construction through innovative technologies, increase productivity and the use of digital design and offsite manufacturing to transform building construction. In July 2018, the House of Lords Science and Technology Committee report "Off-site manufacture for construction: Building for change"(House of Lords, 2018) stated that off-site manufacture (OSM) can help to increase productivity, while reducing labour demand, improving the quality and efficiency of buildings, and reducing the environmental impacts.

In the policy paper "Construction 2025", the UK Government reviewed its construction portfolio (HM Government, 2013, 2017; HM Treasury, 2015). The analysis shows that about half of the projects ends up as residual value in the final product (Bryden Wood, 2017). The analysis clearly identified the reasons for delays causing additional cost. The most significant causes are: (i) poor productivity (accounting for 19%), (ii) operational stoppage (28%), (iii) labour shortage (23%), (iv) lack of materials (8%) and (v) lack of design information (8%). In response to these results, a DfMA-oriented platform for mitigating such issues is currently under development (Bryden Wood, 2017).

Recent publications advocate the adoption of a Design for Manufacturing Strategy (DfMA) as an option to improve the overall assets' performance (Changali, Mohammad, & Van Nieuwland, 2015; Construction Skills Network, 2017; Farmer, 2016; Infrastructure Client Group, 2017; Joshua Southern, 2016; McKinsey Global Institute, 2017; Philipp Gerbert, 2016; Sinclair et al., 2013). According to UK Treasury's Autumn Budget, the Government's adoption of offsite manufacturing in its role as a client will have a lasting impact on the Sector. Major government departments will favour the approach by 2019 (HM Treasury, 2017). Furthermore, according to the Autumn Budget, the UK Government's intent is to prioritise use of offsite manufacturing and other modern methods of construction (MMC) to improve the cost effectiveness, productivity and speed of construction delivery (HM Treasury, 2017).

Since its implementation in the early 1970s, the DfMA approach has proven to provide value maximization in the automotive and aerospace industries (Xie, 2006). In the AEC sector it encompasses a wide spectrum of tools and technologies (both processes and

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products) that help design for ease of manufacturing and assembling of building spaces and components (Bryden Wood, 2017; Building and Construction Authority, 2016). The main goal of DfMA approaches is to work on the relationship between time, cost and quality in the construction industry by eliminating waste or any activity that does not add value to the client, designer or supply chain (Bryden Wood, 2017). The primary objective of such manufacturing-related approaches is to incorporate the knowledge of constructability in the design phase, generating potential savings of approximately 10% in lead time (Russell, Gugel, Radtke, & of Texas at Austin. Construction Industry Institute, 1992).

Despite indications of possible DfMA profit throughout a project's life cycle, typical approaches lack a consistent work methodology and usually focus on the design and planning phases (Nascimento, Sotelino, Lara, Caiado, & Ivson, 2017). Little or no consideration is kept on the construction phase. DfMA, mainly thanks to prefabrication and off-site manufacture in the construction phase, creates opportunities for benefits in several areas, including: (i) shorter overall construction programme, (ii) certainty of programme, (iii) safety, (iv) quality, (v) sustainability, (vi) procurement (Bryden Wood, 2017; Building and Construction Authority, 2016; Sinclair et al., 2013). It is anyway true that not all the advantages of the above approach are fully achieved. Even if possibilities exist when using modern methods of construction (MMC), processes and delivery platforms are not structured to carry out the expected benefits. This is mainly due to existing design processes and procurement methods, which do not integrate efficiently with manufacturing approaches (Arayici et al., 2011; Hamdi & Leite, 2012; Oskouie, Gerber, Alves, & Becerik-Gerber, 2012; R. Sacks, Treckmann, & Rozenfeld, 2009).

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With the objective of bringing clarity in the currently available processes and to develop an integrated workflow model, this research presents a critical analysis of three existing design processes. The first two have been selected as they represent the state of the art of the most integrated design processes with DfMA principles, while the third one represents the process that supported the case study: RIBA Plan of Work 2013, Singapore BCA's DfMA for BIM, and the Italian public procurement process.

The critical analysis conducted focused on the possibilities and limitations to meet with DfMA requirements and activities. To support the research and to validate the critical analysis conducted, a case study is analysed in its DfMA peculiarities, focusing on one sub-system manufactured offsite. The case study consists of a kindergarten in central Italy (1,673 m^2). Among all the offsite manufactured sub-assemblies potentially applicable to the project, the focus has been on the bathroom pods. The reason for this choice is related with the amount of production information and data available, thanks to a direct cooperation with the manufacturer. The main goal is to conceptualise the flow of information requirements, together with their commitment timeline, in order to set sufficient knowledge for a DfMA-oriented procurement. Whilst the study has been focused on the bathroom pods sub-assemblies, the outcome of the research can be extended to the whole building.

For the case study presented in this paper, the DfMA approach is enabled by BIM, engaging contractors, suppliers, sub-contractors, and other specialist engineers earlier in the design phase. This can help to merge inputs and requirements of downstream players with those upstream in an information pull strategy (Al Hattab & Hamzeh, 2015). In this research area, benefits of pull-flow processes (LPS, KanBIM, VDC, Obeya Room, etc) have been underlined in several researches (Arayici et al., 2011; Gerber, Becerik-Gerber, & Kunz, 2010; Gurevich & Sacks, 2014; He & Wang, 2015; Jeong, Chang, Son, & Yi, 2016; Li et al., 2018; Liu & Shi, 2017; Mahalingam, Yadav, & Varaprasad, 2015; Mandujano, Alarcón, Kunz, & Mourgues, 2016; Onyango, 2016; R. Sacks et al., 2009; Rafael Sacks, Barak, Belaciano, Gurevich, & Pikas, 2013; Rafael Sacks, Radosavljevic, & Barak, 2010; Tezel, Algan and Aziz, 2017; S. Zhang, Teizer, Pradhananga, & Eastman, 2015).

Methodology: frameworks comparison and process matrix

The research starts with the review of the three existing frameworks: (i) RIBA Plan of Work 2103, (ii) Singapore BCA's DfMA for BIM and (iii) Italian public procurement procedure, from now on respectively RIBA, BCA, ITA. The methodology carried out is presented in Figure 1 [place Figure 1 here].

The objective is to compare and to identify all the key rules, activities and milestones required to ensure that a successful DfMA approach is achieved with a focus on the Italian market. The result is an enhanced information workflow developed as a revisited design process and summarised in a Process Matrix. In fact, the review consisted in mapping the activities of each stage in the frameworks, focused on the stages' objectives. It is assumed that collaboration rules and interoperability standards across disciplines (necessary for a DfMA approach) will be incorporated in the BEP (BIM Execution Plan) and Strategy Brief, but for the scope of the research neither actors' role, interaction methods or information exchange methods are considered.

The analysis of existing workflows is carried out by means of a process map. Process mapping is a solid and recognized approach to design and visualize workflows of a business process model (Seghezzi & Masera, 2016), providing scientific basis to decision-making and increasing transparency (Lee, Liu, Chunduri, & Solnosky, 2014).

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Construction projects mapping is particularly challenging due to the features of the construction sector. AEC industry is mainly experience-based, composed of small firms (especially in the Italian framework); nonetheless, a more scientific approach in this sense could result in useful outcomes in terms of knowledge management, and therefore higher quality (Woo, Clayton, Johnson, Flores, & Ellis, 2004).

Process maps usually include a huge amount of information related to the engaged actors, the operations that should be carried out, the decisions guiding the process, inputs and outputs, articulated in processes and sub-processes. In this case, a process matrix is presented to provide a simplified and more accessible framework (Governo della Repubblica Italiana, 2016; He & Wang, 2015; Li et al., 2018; Liu & Shi, 2017; Mandujano et al., 2016; Onyango, 2016; Robichaud & Anantatmula, 2010; Rafael Sacks, Koskela, Dave, & Owen, 2010; Tezel, Algan and Aziz, 2017; Voss, Jin, & Overend, 2013; Woo et al., 2004; S. Zhang et al., 2015; Robichaud & Anantatmula, 2010; Rafael Sacks, Koskela, et al., 2010); the matrix includes the main stages of the process, the activities to be carried out, the objectives to be reached for each of the phases, with a special focus on required activities for a BIM for DfMA perspective. For each stage of the process, required data and model development level are provided.

The use of this process matrix is useful to keep trace of information flows through the entire process, and could be used as a management tool in further steps of design and construction (Voss et al., 2013). Once a merged framework is outlined, the chosen sub-system (bathroom pod) is used to validate the information requirements throughout each stage of the design-to-construction process.

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Existing framework review

The legislative framework in Italy is set mainly by D.Lgs. 50/2016 as amended and D.M. 560/2017 (Governo della Repubblica Italiana, 2016; Ministero delle Infrastrutture e dei Trasporti (MIT), 2017), and currently under implementation. Public projects should be designed following three degrees of development: (i) Technical and economic feasibility, (ii) Concept Design, (iii) Technical Design. It is to notice that the specific requirements for these stages are not the same for their RIBA namesakes. The contents of the three Italian stages are established by a regulation draft (Schema di Decreto Ministeriale recante "Definizione dei contenuti della progettazione nei tre livelli progettuali"), released in May 2018 and currently undergoing a public consultation procedure (Ministero delle Infrastrutture e dei Trasporti (MIT), 2018).

The frameworks are presented firstly at their upper level, as in Figure 2. The different level of granularity for the three processes is the first observation. After that, a comparison of the frameworks is produced to better identify differences and similarities in the objectives of each stage.

The comparison of frameworks aims to outline the stages and their contents which best fit a DfMA approach. For this purpose, similarities are highlighted among each phase's contents and high-level expected deliverables. For the comparison, the authors evaluated seven categories which are reported across each of the three frameworks, with diverse timing and weight. Other than common interest areas (Feasibility, Strategy, Objectives, Time and Cost), two more DfMA-peculiar categories are highlighted: Contractor/Supply Chain integration and Evaluation of alternative strategies. The process ends with the following areas of investigation:

(1) Strategy;

(2) Objectives;

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(3) Interaction with contractor/supply chain

(4) Alternative solutions

(5) Budget

(6) Feasibility studies

(7) Time schedule

In the Process Matrix presented in Table 1, the objectives of the various stages are presented exactly as they are listed in each official framework. Then, to identify relationship across the three contexts, a superscript is given as follows:

- [a] When strategy is outlined, in terms of qualitative and quantitative need for the business case;
- [b] When objectives are outlined;
- [c] When Contractor / type of contract is firstly considered;
- [d] When alterations to the strategy / possible alternative design solutions are considered;
- [e] When project budget is explicitly mentioned for the first time;
- [f] When feasibility studies are conducted;
- [g] When time schedule is defined for the first time.

The three frameworks follow different deliverables structures. In fact, it is important to notice that the superscripts never represents a full correspondence of deliverables and stages' outcomes. For example, inside the RIBA's Stage 1 "Preparation and Brief", Handover Strategy and Risk Assessment are a suggested task; the BCA's Stage 1 "Project Brief Development" focuses instead on BEP (BIM Execution Plan) and a Brief Compliance Plan to meet client's requirement, never mentioning risk assessment or post-completion activities.

Finally, the Italian preparation stage, composed by "Quadro Esigenziale" and "Documento di Indirizzo alla Progettazione" (QE and DIP), is part of a regulation which is going through its fourth review (as of January 2019), therefore this document is not yet definitive neither approved.

Proposed framework – process matrix

The case study is built upon a 1,673 m^2 kindergarten in Italy. The existing Italian public procurement process (made of three stages before construction) is not designed to be aligned with a DfMA approach. To keep changes constantly and frequently under control, means such as concurrent engineering, multidisciplinary review of design and manufacturers integration need to be implemented into a structured process, through articulated stages (Love, Gunasekaran, & Li, 1998; Motawa, Anumba, Lee, & Peña-Mora, 2007). If the project stages are too broad, the risk to identify a possible threat late in time is high. The design may vary drastically within the same stage, making every change to the design increasingly expensive (Pan & Sidwell, 2011). On the opposite side, a deep breakdown of the project phases (i.e. 8 for RIBA) might increase the complexity of managing information (Voss et al., 2013). While this might be necessary for complex or large-scale interventions, the chosen case study (a relatively small kindergarten) could suffer from over-processing of information and not-needed repetitive tasks. For these reasons, the framework adopted is similar to the Singapore one. In fact, it is based on six stages, as showed in the Process Matrix provided in Table 2.

The table shows the adopted framework which is divided in six stages (i-column). In each stage one or more steps (ii) summarize the expected goals. Then, the main objectives (iii) are identified together with the information modelling actions (iv) required to produce DfMA outcomes. Finally, under the data/model development column (v) the required model actions are summarized. In the Case Study development chapter, this last column (v) will incorporate the specific description of the geometrical and non-geometrical information delivered at each stage for the chosen sub-system (Bathroom Pods).

Case study application: overview

The case study project consists of a kindergarten located in the province of Rimini (Central Italy). The project area is 12.550 m^2, and it is currently used as a garden by two schools already existing in the area. The plot has two different accesses: one by the bicycle and pedestrian path and the other for cars and school buses.

This configuration defines an axiality among the main accesses, also integrated with the existing schools. The spaces are distributed starting from this axiality: four classrooms (called Home-Base); a canteen; an atelier with filtered access; and an administrative space. This aggregation generates a space between the modules, called Agorà, protected by the rest of the park with low and deep vegetation barriers, and then covered by a structurally independent canopy. The latter is developed by the repetition of frame modules, and it is accessible by the children for some parts (Figure 3). Each Home-Base is a structurally independent cell made of prefabricated timber-frame closed panels, laid on a concrete mat foundation. Each Home-Base (Figure 4) is about 130 m2, with a 20 m^2 porch on each short side, a 50 m^2 classroom space, and the rest occupied

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by the integrated bathroom (two coupled bathroom pods), a small technical room, and a buffer space facing the entrance.

Spatial design for this type of building in Italy must comply with various regulations and guidelines (D.M. 18-12-1975, L.23/1996, MIUR Guidelines 2013). These general guidelines were then crossed with requirements expressed by an innovative Pedagogical Plan. Due to these precise needs, the DfMA process is tested on a very specific set of design requirements, proving its flexibility.

Sub-system description

The Bathroom Pod (Figure 5) is the sub-system that was chosen to test the proposed Process Matrix and its DfMA-related information flow. A co-operation with three manufacturers was established, through factory inspections and meetings with the companies' technical departments about production techniques. Two main types of bathroom pods were identified: (i) the first with precast concrete modules and (ii) the second assembled with lightweight panels made of steel profiles and plasterboard panels. The choice between the two technologies is due to the project's characteristics, on a case-by-case basis. For the case study the chosen technology is the lightweight one (ii), due to its greater compatibility with the building's timber frame structure.

For the lightweight type, the Pod is composed starting from a reinforced concrete base (of variable thickness) cast in a galvanized-steel frame. Walls and ceilings are made of structural steel frame panels, inside which plumbing pipes and electrical ducts are arranged, and closed on one side with panels of variable materials according to specific needs (plasterboard panels for the case study). During the production process, the cell is constantly subjected to a series of structural and QA tests.

Research results and discussion: bathroom pods' case study

In order to test the proposed Process Matrix on the case study presented above, each stage has been enriched with the outcomes of the application of the process in the design of the Bathroom Pods. While a good set of data was available for the design stages, the stages from pre-construction to post-completion have been mainly supported by experience-based information (Table 3).

Stage 1 – Project brief

In this phase the project strategy is recorded formally. No model data is produced at this stage, but the development flow of the information model is decided.

(1) Requirements are collected from the Client. Among them, the ones involving bathroom spaces are studied. To plan what information will be provided at each stage, a hierarchy across client's requirements is established. For bathroom spaces, the hierarchy followed this pattern: (i) object geometry, (ii) relationships with adjacent spaces, (iii) frequency, (iv) complexity (e.g. finishing materials, required power, equipment, etc.). This classification, which may vary case-by-case, happened before any optimisation attempt.

(2) A primary difficulty is represented by the colloquial form of the requirements.

(3) The design team was required to create a structure into which the client could enter data for the different stages of model development, as shown in Table 4.

(4) After the structure, the content of requirements is analysed. Rarely these are already complete, so the Design Team had to add new attributes among the properties of the bathroom space (e.g. acoustic and thermal comfort, air quality, fire safety and other properties established by the regulation).

(5) To create the structure for the requirements, a spreadsheet has been chosen. This data structure facilitates both the contribution of the client in this stage and the future integration with the objects of the BIM model.

(6) A formal pre-contract BEP is not proposed by the client. For the scope of the case study, information exchange methods and timing and level of geometrical and non-geometrical detail are established.

Stage 2 – Concept design

The project is described at a range of scales, from facility level down to individual components. The Process Matrix also moves between different levels of detail. In this phase, spaces represent the first driver with which to evaluate the degree of DfMA adoption on the project. To develop specific solutions, the Supply Chain integration is also defined.

(1) A data template, in the form of a spreadsheet containing the agreed attributes, is loaded into the model and linked to a parametric mass volume (i.e. placeholder). The information incorporated in the placeholder object for Stage 2 are: dimensions, consequent area and volume, and fixtures. Requirements are imported directly from the spreadsheet produced in the previous phase. Having spaces quickly modelled as massing placeholders allowed early optioneering to happen (Figure 7), and the parametric data paired with objects allowed immediate validation via Brief requirements schedules. This step is what BCA defines Brief Compliance Plan (Building and Construction Authority, 2016). It is used to eliminate unwanted design changes when optioneering occurs, and it is obtained through automated or semi-automated comparison between the proposals that emerged and the brief's requirements. As the image above shows,

the Employer Information Requirements (EIR) schedule for bathroom spaces (already in place since Stage 0) is used. To facilitate the inclusion of DfMA solutions, adoption of modular grids and a consistent range of floor to ceiling heights is recommended. One of the two pod's clear dimension is asked to be within 240 cm and the floor-to-ceiling height of maximum 240 cm. The reason is to facilitate transportation in case the bathroom is actually prefabricated. These dimensions allow transportation within Italian restrictions for regular shipments (max width of 255 cm), whether the bathroom is procured as volumetric unit or kit-of-parts panels. Having a clear height of 240 cm allows MEP systems to run above the bathroom.

(2) Then, different layouts are experimented. Each time the bathroom space is modified, its data change accordingly. This allowed the Team to export bills of quantity for validation purposes. A data-rich model of spaces is used to filter all bathrooms and classrooms to check and validate the adjacency requirement, before entering the next stage. Early data-sheet are generated from objects (e.g. clear height, spaces areas, finishing) for approval. Note that at this phase no technical solution or specific technology (i.e. Bathroom Pods) is mentioned yet.

(3) Flows in the building layout are analysed, and a first library of space is created. A design review at this point helped to identify standardisation opportunities and a list of possible sub-systems to be standardised is created. The bathroom is one of the elements emerging from this process. The rules for the creation of parametric components are presented in detail in the next paragraph, Stage 3 – Detailed Design. The series of elements developed through the process described above are used to communicate the standardisation intent to the

Supply Chain. So, a first Supply Chain engagement happened at this Stage (Stage 2).

Stage 3 – Detailed design

The goal of this Stage is to identify technical solutions and test them over DfMA requirements, with feedback from Supply Chain and/or Contractors (if the process allows it). By the end of this phase, detailed parts are studied, and data-rich models generated. Once objects are created, grouped, linked with bills of quantity and when the first optimisation took place, a team of consultants studied the outcomes to propose different technical solutions. In the case study, consultants highlighted the Bathroom Pods techniques.

(1) The layout diagram showed some opportunities for space rationalisation. At this point for the first time, the Bathroom Pod technology was proposed.
(2) Meetings with pod manufacturers helped to understand the rules under which these objects are designed, fabricated and installed. The need for a manufacture-ready tool (and people able to use it) arises here in order to design the components required to assemble the pod.

Sub-system investigation

With the help of the manufacturer and specialist consultants, the detailed design focused on:

- Pod's size and shape (for transportation, stocking and lifting issues);
- Weight and overall dimensions (for efficient hoisting and installation);
- Assembly details (e.g. hoisting mechanism, production tolerances, lifting strategy). In doing this, attention is shifted from material layering in favour of

components' joints. This is a peculiarity of DfMA solutions. Performances are guaranteed within the module due to its factory quality testing, but greater attention is placed where modules come together.

Investigated areas of the sub-system are Structure, MEP, Connection and Joint details.

The weight of prefabricated sub-systems is checked against structural strength of the receiving platform and lifting feasibility. Another structural consideration on Pods is related to design aspects. Each Pod is self-bearing but it requires testing against external loads. During spaces aggregation and optimisation (happened at Stage 2), all bathrooms are moved away from building's perimeter for this reason. Integration with diagonal wind-bracings to resist horizontal loads would have taken the production process to last 25%÷80% longer (from 16 man-hours for traditional Pod to 20÷29 man-hours for bracings Pod), with an increase in production costs.

One important solution implemented in the BIM model is the so-called no-fly zone. Above the Pods some space is kept free from obstruction to allow main air-ducts to run through and to guarantee enough room for modules connection operations. These no-fly zones are modelled as masses, for geometrical clash detection.

Particular attention is used on Pod's finished floor level, which must flawlessly match the finished floor level outside the bathroom. For this purpose, the screed hosting the Pod is modelled with a customised socket that serves the purpose. Being the bathroom space (675x240cm) obtained coupling two units (unit A: 480x240 cm, unit B: 195x240 cm), specific attention is given to the joint between the two modules.

(3) As the stage proceeds, assigned parameters are validated and additional data is assigned to components for the use of downstream activities (i.e. costing,

scheduling, fabrication, facility management) (see Table 5). This allowed more accurate quantity take-off, enabling precise cost estimation and materials inventory for the production process management. An example is given by aluminium C-shape profiles for the panels' substructure. Each profile will be fabricated by the manufacturer starting from an aluminium coil, using a CNC machine. The manufacturer can precisely calculate how much aluminium and time is needed to fabricate each Pod's substructure. Additionally, raw material's price input gives back to the manufacturer the aluminium cost for the entire lot of Pods.

Stage 4 – Pre-construction

In this Stage, the digital model is refined to incorporate inputs from manufacturer and develop assembly sequences, as well as construction programme documentation.

(1) The Manufacturer suggested the possibility to realise technical drawings of C-shape profiles that are CNC-ready. The file could be directly uploaded into computers to start bending aluminium coils. To obtain this, the design team was required to work with manufacture-field software (i.e. SolidWorks, Inventor, etc.). The expected advantages were a library of data-rich elements for designers, and fabrication-ready components for the manufacturer's technical department. The success of this process is strictly depending on the close collaboration between the design team and the specialists, while an interruption in the communications or data flow may interrupt this process.

(2) Since each bathroom is composed of two adjacent modules, the set-up will happen in three phases: (i) site preparation, (ii) module A and B placement, (iii)

connection of air, electrical, water and disposal systems. The assembly sequence has been planned but not simulated within the model. The reason is the lack of equally detailed information for the rest of the building's elements (not subjected to DfMA focus). In fact, to perform a credible simulation all the sub-systems involved should have a similar level of detail.

(3) Production commencement and ordering time are evaluated thanks to data incorporated into components (Figure 8). The Pod's manufacturer is asked to validate procurement, timescale assumptions and feasibility of proposals. Among the benefits of collaboration are: (i) analysis of site constraints, which resulted in a different assembly method (top lifting instead of side taxiing for which there was no room); and (ii) validation of estimate production time. For this purpose, different manufacturing phases are considered (product design, raw material purchase and supply, fabrication and QA, shipment). The incidence of each phase changes in relation to manufacturing strategies (e.g. sequence or parallel), but the entire process is estimated in 12÷14 weeks from order to delivery onsite. Average incidence of each sub-phase is 55% for design and prototype, 32% for fabrication and transportation, 13% for set-up and connection. The same data is used by manufacturer to estimate its production rate. At operating speed, up to 10 modules a day can be manufactured.

Stage 5 - Construction

In the case study used for the test, the construction stage did not take place, however some general considerations were made based on experience (Figure 9):

(1) The two phases of offsite fabrication and onsite assembly are planned to take place in parallel. For this purpose, the incidence of production time is evaluated for the prefabricated sub-systems – including Bathroom Pods.

(2) Time data embedded into components could potentially allow planning of Just-in-time logistic, but the BIM model was never imported into construction management and planning tools to study delays and storage periods of goods.

Stage 6 – Post-completion

The client's requirements on this aspect were not defined. There was a general statement indicating the need for low lifecycle costs, but no specific attributes. This represented a challenge throughout the whole process, mainly because – even if components are designed and possibly manufactured after a BIM model – the data structure may not match the operator's specifications. These missing procedures limited the team's work to simply linking elements with their IDs (for easier identification in case of replacement).

Conclusions and further steps

The core characteristic of DfMA is its component driven, modularisation and standardisation approach (Building and Construction Authority, 2016). DfMA also requires planning, adapting and optimising the design to leverage off-site fabrication of components and on-site assembly (Building and Construction Authority, 2016; McFarlane & Stehle, 2014; Sinclair et al., 2013). Hence, the use of Building Information Modelling (BIM) as integrated collaborative environment can drive the overall process and provide further potential benefits. Studies about BIM-Lean Construction have been reviewed (Gurevich & Sacks, 2014; Rafael Sacks et al., 2013; Rafael Sacks, Bhargav, Koskela, Owen, & Dave, 2009; Rafael Sacks, Koskela, et al., 2010; Rafael Sacks, Radosavljevic, et al., 2010) and the evidences claim that BIM is able to make the process lean. Since its application guarantees the fulfilment of several Lean Construction objectives (Ningappa, 2011), it can be shaped as a lean process itself (Onyango, 2016). BIM could help merging inputs and requirements of downstream players with those of the upstream in an information pull strategy (Al Hattab & Hamzeh, 2015). In this research area, the benefits of pull-flow processes (LPS, KanBIM, VDC, Obeya Room, etc) have been underlined in several research works (Arayici et al., 2011; Gerber et al., 2010; Gurevich & Sacks, 2014; He & Wang, 2015; Jeong et al., 2016; Li et al., 2018; Liu & Shi, 2017; Mahalingam et al., 2015; Mandujano et al., 2016; Onyango, 2016; R. Sacks et al., 2009; Rafael Sacks et al., 2013; Rafael Sacks, Radosavljevic, et al., 2010; Tezel, Algan and Aziz, 2017; S. Zhang et al., 2015).

The integration between BIM based processes and DfMA principles is therefore a promising application; due to its innovative impacts, a framework to guide designers and suppliers is recommended. The proposed framework is the result of a literature review of existing DfMA frameworks and of the comparison with the traditional Italian design process. As a result, a 6 stage framework has been developed and adapted to the Italian AEC sector, with the aim of structuring and guiding the application of DfMA in BIM processes. The framework has then been tested on a case study located in Italy.

Case study limitations

Through the framework application to the case study some limitations have been highlighted:

(1) Background. In this case, the involved Supply Chain (SC) is represented by Italian trade contractors, and the framework is therefore suitable for Italian

context. Further applications to other Countries should require an analysis of capacity and capability of SC.

(2) Procurement process. The proposed framework has been developed considering public procurement: this choice is related to the current lack of structure of private procurements, that are therefore harder to track.
In Italy, public procurement processes are structured in three main stages; this setting could be too general to accommodate information management within phases. From the beginning to the end of the same stage the object might change drastically. A relatively more structured process (as the UK or Singapore processes) might allow deliverables to be checked frequently and constantly, with means such as design-freeze and/or simultaneous engineering. It is relevant that Italian legislation is under development in this sense, also due to the growing introduction of BIM-based approaches in public procurements.

(3) Application. The UK and Singapore Government platforms and frameworks have been deeply analysed and used as a guide to develop a framework suitable for the Italian situation; it is relevant to underline that those documents were developed for a different context. A comparison of these frameworks has been provided.

These limitations show that, while the proposed framework was developed for the Italian context, it could be implemented in other Countries as well. Considering that Italian legislation for public procurements is currently undergoing deep changes, due to the introduction of BIM processes, the proposed framework should in future be adapted to new legislation in this sense.

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Edges and gaps

Innovation and limitations related to each of the proposed stages are defined in this section, with the exception of Stage 6, that was not defined.

Stage 1

The main current gaps that should be overcome in this phase (see Table 6):

- Computational setting of requirements: this aspect requires a change in traditional approach between designers or consultants and the client
- Whenever requirements are not defined via a formal structure, there might be the need of a data-modelling activity to go from plain-language to structured-language. This could potentially cancel the time advantages of an automated checking
- This shift requires that both clients (with the EIR) and suppliers (with BEPs) are instructed to set solidly structured data.

Stage 2

The main current gaps related to this phase are expressed in Table 7 and can be described as:

- the need to encourage SC integration in contracts;
- the design of components has to be carried out together with SC experts or manufacturers, in order to provide a successful standardisation and buildability;
- RDL must be compliant with EIR specifications.

Stage 3

The main current gaps related to this phase are expressed in Table 8 and can be described as:

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- the deep and complex relation between building design on the one hand and manufacturing on the other hand;
- the adoption of a DfMA approach requires knowledge of manufacture-field tools and procedure;
- the identification and development of technical solutions require strong integration with Manufacturers.

In this sense, the creation of a platform that potentially crosses many sectors would be efficient and provide storage of components' libraries. In this case, data sharing among stakeholders should be allowed to effectively store and analyse component's libraries.

Stage 4

The main current gaps for this phase, identified in Table 9, are the following:

- the need to provide an efficient and complete BIM-DfMA integration, with an optimization of the integration between BIM models and CNC models (i.e. the avoidance of 2D extraction is preferred);
- the need to investigate the integration of DfMA and non-DfMA components and solutions. In fact, it is relevant to underline that not all the components can be produced in a DfMA approach.

Stage 5

The main current gaps for this phase are provided in Table 10 and are the following:

- the integration between DfMA and non-DfMA parts of the project shall be considered in the construction programme;

- an evaluation of the Supply Chain shall be performed.

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Table 1. Comparison of existing frameworks.

RIBA	BCA	ITA
Strategic definition	**Project brief**	**Preparation (QE*+DIP**)**
Identify: • client's business case [a] • client's strategic brief [b] • other core project requirements	• Establish BIM strategy [a] • Identify desired BIM outcomes [b] • Agree on data extraction requirements	Identify: • general objectives [b] • core requirements for the intervention [a] • specific qualitative and quantitative needs for the intervention [a] Establish: • desired levels of performance/service [a] • design phases and relative schedule • criteria for contractor's selection • type of contract [c]
Preparation and Brief	**Concept design**	**Technical/economic feasibility**
Develop: • project objectives; • quality objectives; • project outcomes [b]; • sustainability aspirations; • project budget [e]; • other parameters or constraints • initial Project Brief [a] Undertake: • feasibility studies [f]; • review of site information.	Ensure consistency between design, specifications and client's brief [d]	Defines objectives and characteristics to be implemented, by: • identifying possible alternative design solutions [d] • analysing also the non-realization of the intervention "zero option" Develop: • feasibility document of design alternatives [f]
Concept design	**Detailed design**	**Developed design**
Outline: • proposals for structural design and building services systems; • specifications and preliminary Cost Information [e]. • relevant Project Strategies in accordance with Design Programme [g]. Agree: • alterations to brief [d] Issue: • final Project Brief	Enable identification of Contractors, Procurement Routes and Supply Chain [c]	Based on the technical and economic feasibility project, it identifies: • the work to be carried out, in compliance with QE and DIP • the time schedule of the various implementation phases [g] • definitive quantification of budget [e]

Developed design	Pre-construction	Technical design
Prepare: • coordinated and updated proposals for structural design and building services systems; • specifications, Cost Information [e] and Project Strategies in accordance with Design Programme.	• Confirm Stage 3 fully conforms to client's brief • Verify Stage 3 allows calculation and approval of project agreed maximum price [e]	• Based on Developed design, it identifies: • in every detail the work to be carried out • relative cost foreseen [e] • time schedule consistent with that of the Detailed design: • Each element in form, type, quality, size and price; • a special maintenance plan for the whole intervention and its parts, for the entire life cycle
Technical design	**Construction**	**Construction**
Prepare: • Technical Design in accordance with Design Responsibility Matrix and Project Strategies Include: • all architectural, structural and building services information; • specialist subcontractor design and specifications, in accordance with Design Programme [c]	Enable construction to happen in line with project brief requirements	// Not formalised//
Construction	**Post completion**	**Post completion**
In accordance with Construction Programme: • Offsite manufacturing; • Onsite Construction; • resolution of Design Queries from site.	Represent the as-built asset (including installed systems)	// Not formalised //
Handover and Close-out	**-**	**-**
• handover of building • conclusion of Building Contract.	-	-
In use	**-**	**-**
undertake In Use services in accordance with Schedule of Services	-	-

*QE: Quadro Esigenziale (Framework of the requirements). Includes: high-level objectives, basic requirements; quantitative and qualitative needs for the intervention

**DIP: Documento di Indirizzo alla Progettazione (Document for design orientation). Includes: as-is conditions of the places; needs to be met; general objectives; performance levels; technical requirements; levels of the design development and relative schedule; drawings and documentation; cost estimation, sources of funding and the financial limits; procedure for contractor selection; award and assessment criteria; type of contract.

Table 2. Process matrix expressing the proposed framework.

	Step(s)	Objective(s)	BIM for DfMA actions	Data/Model Development
1 Project Brief	• Project Scope and objectives	• Establish strategy • Identify desired outcomes • Agree on data extraction requirements	• Capture rules for DfMA adoption (modular floor heights, grid dimension, etc.); • Develop BIM and DfMA implementation strategies and incorporate into BEP.	• No data yet. Time for data-flow definition
2 Concept Design	• Develop and test the system	• Confirm proposal meets the brief	• Building massing studies (orientation, area, volume, etc) based on site constraints and client/authorities' requirements; • Develop parametric "placeholders" objects for spaces with modular grids and layout; • Use space objects to generate design optioneering to find best fit to project brief; • Generate room data sheets from space objects for approval of functional, environmental and finishes requirements; • Use model to show concept for stakeholders' feedback.	• Include information such as massing (overall volume), space allocation (e.g. room size) and site location (e.g. northings and eastings)
3 Detailed Design	• Production design for fabrication • Prototype (*) • Early adopters' involvement (*)	• Confirm fully brief conformity • Enable identification of Contractors and Supply Chain	• Add more details to space objects (both geometry and data); • Use objective analysis and reporting tools to demonstrate brief objectives are achieved; • Validate DfMA solutions through early contractor and supply chain engagement; • Generate detailed part and whole models for different disciplines for early coordination.	• Include accurate data and represent technical solutions (not commercial)
4 Pre-Construction	• Design analysis	• Confirm fully brief conformity; • Verify Stage 3 allows calculation	• Refine models to incorporate inputs from DfMA Supply Chain;	• Include highly accurate info from supply chain. Can be used for

	• Whole life tools (cost & carbon)	and approval of project agreed maximum price	• Develop overall construction programme schedule and assembly sequencing; • Develop fabrication and installation sequences, method statements, resource management plan, etc. • Generate digital prototypes to verify construction strategy.	prototyping, first run studies and planning construction activities (e.g. VDC)
5 Construction	• Training • Virtual Building • Fabrication Model Workflows (**)	• Enable construction in line with project brief requirements	• Generate shop drawings for fabrication from models OR integrate fabrication with models; • Track construction activities and resources based on planned programme and planned assembly sequence; • Validate installation onsite and update as-built model.	• Incorporates amendments and lessons learned from previous stages. The model is extremely accurate and can be used for construction
6 Post-Completion	• LC costs • FM attributes	• Represent the as-built asset	• Ensure that as-built models are up-to-date for handover; • Integrate as-built model with FM system.	• Represent the building in use, including feedback info from BMS and FM. The model is up-to-date and will continue evolving over time

Table 3. Process matrix implementation with case study.

Stage		Step(s)	Objective(s)	Case Study application
1	**Project Brief**	• Project Scope and objectives	• Establish strategy; • Identify desired outcomes • Agree on data extraction requirements	• Requirements for bathroom spaces are extracted
2	**Concept Design**	• Develop and test the system	• Confirm proposal meets the brief	• Bathrooms created as volumetric masses placeholder enriched with data • First optimisation attempts take place • Spatial diagrams are generated, supporting grouping and rationalisation of spaces
3	**Detailed Design**	• Production design for fabrication • Prototype (*) • Early adopters' involvement (*)	• Confirm fully brief conformity • Enable identification of Contractors and Supply Chain	• Consultants study the outcomes of previous stage to propose different technical solutions (Bathroom Pods first highlighted) • Rules for Bathroom Pods design are defined • Pod's size and shape are tested with Supply Chain • Weight and overall dimensions are checked • Assembly issues are considered • Assigned parameters are constantly tested • Data for downstream activities (e.g. costing, scheduling, fabrication, facility management) are assigned to components
4	**Pre-Construction**	• Design analysis • Whole life tools (cost & carbon)	• Confirm fully brief conformity; • Verify Stage 3 allows calculation and approval of project agreed maximum price	• Fabricators test the capability to input BIM model's element directly into CNC machines • The Pod's installation sequence is simulated within the model • Production commencement and ordering time are evaluated thanks to data incorporated into components
5	**Construction**	• Training • Virtual Building • Fabrication Model Workflows (**)	• Enable construction in line with project brief requirements	• The incidence of production time on overall programme is evaluated for prefabricated sub-system, including Bathroom Pods • Just-in-time logistic is simulated via time data embedded into elements
6	**Post-Completion**	• LC costs • FM attributes	• Represent the as-built asset	• The elements' maintenance and replacement operations are considered during the design phase (floor slope and waterproofing layer are factory-built and tested, each supply pipe is made accessible for inspection) • Elements are paired with IDs to facilitate localisation and replacement • O&M manuals are provided supported with digital models

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Table 4. Student's bathroom EIR schedule

St.	SCOPE	PARAMETER	REQUIREMENT
2	D&L	Max clear width	240 cm
		Max internal height	240 cm
		Bathroom is in direct communication with classroom	
	FIXTURES		- n° 4 toilet bowls; - n° 1 toilet bowl for disabled people; - n° 3 grounded lavatories; - n° 1 lavatory for disabled people; - n° 1 mirror cm. 100 x 100; - n° 1 mirror cm. 400 x 100
3	SYSTEMS		- n° 4 ceiling lights, low-consumption; - n° 3 wall lights, low-consumption; - n° 6 electric plugs; - n° 1 intercom line plug; - n° 1 vacuum cleaner plug; - n° 6 hot/cold water plugs; - n° 4 toilet sewer.
	COMFORT	PR_RA01 – Acoustic comfort control	
		PR_RA02 – Thermal comfort control (winter)	
		PR_RA03 – Thermal comfort control (summer)	
		PR_RA04 – Air quality control	
		…	
	SAFETY	PR_RA 08 – Fire safety control - Compartmentalization	
		PR_RA 09 – Fire safety control - Extinguishment	
		PR_RA 10 – Fire safety control - Detection	
		…	
	ASPECT	PR_RA 15 – Walls	
		PR_RA 15 – Floors	
		PR_RA 15 – Ceilings	
4	OTHER (DfMA)	Maintenance	
		Fabrication time – expected	
		Fabrication time – effective	
		Assembly Time – expected	
		Assembly Time – effective	

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Table 5. Student's Bathroom EIR schedule (implemented).

Bathroom Pod – CB01			
St.	**SCOPE**	**PARAMETER**	**REQUIREMENT**
2	D&L	Max clear width	240 cm
		Max internal height	240 cm
		Bathroom is in direct communication with classroom	
	FIXTURES		- n° 4 toilet bowls; - n° 1 toilet bowl for disabled people; - n° 3 grounded lavatories; - n° 1 lavatory for disabled people; - n° 1 mirror cm. 100 x 100; - n° 1 mirror cm. 400 x 100
3	SYSTEMS		- n° 4 ceiling lights, low-consumption; - n° 3 wall lights, low-consumption; - n° 6 electric plugs; - n° 1 intercom line plug; - n° 1 vacuum cleaner plug; - n° 6 hot/cold water plugs; - n° 4 toilet sewer.
	COMFORT	PR_RA01 – Acoustic comfort control	Class 1
		PR_RA02 – Thermal comfort control (winter)	Class 0
		PR_RA03 – Thermal comfort control (summer)	Class 0
		PR_RA04 – Air quality control	6 l/s·person
		…	
	SAFETY	PR_RA 08 – Fire safety control - Compartmentalization	Class 0
		PR_RA 09 – Fire safety control - Extinguishment	Class 0
		PR_RA 10 – Fire safety control - Detection	Class 0
		…	
	ASPECT	PR_RA 15 – Walls	Tiles
		PR_RA 15 – Floors	Tiles
		PR_RA 15 – Ceilings	Plaster
4	GEOMETRY	Width - external (mm)	2400
		Width - internal (mm)	2260
		Height - external (mm)	2550
		Height - internal (mm)	2400

		Length - external (mm)	4800
		Length - internal (mm)	4660
		Weight (kg)	2898
	DfMA	Maintenance	Class 1
		Fabrication time (hours) – estimated	16
		Fabrication time (hours) – final	
	COST	Pod’s final cost (€) – estimated	9290
		Pod’s final cost (€) – final	
		Transportation cost (€) – estimated	152
		Transportation cost (€) – final	
	ASSEMBLY	Assembly time (hours) – Expected	1
		Assembly team (persons)– Minimum	3
		Assembly equipment	Auto crane
		Predecessor activity (WBS)	
		Following activity (WBS)	
		Other requirements	

Table 6. Stage 1 edges.

Main recipient(s)	Edges	
Client and FM	*Data definition*	Great attention has been denoted to present and future data uses and values; data structure is set from early stages
Client and designer	*Needs definition*	The client's needs and requirements are formalised in a structured and computational way from the very early beginning. This enhances the possibility of a structured strategy and of prioritization of requirements for the client.
Designer	*Compliance Plan definition*	Automation in this phase can help designers to get an immediate feedback from the client
Suppliers	*Anticipation*	This strategy allows the setting of a proper pre-contract BEP

Table 7. Stage 2 edges.

Main recipient(s)	Edges	
-	*Supply Chain integration*	The creation of design alternatives can be faster and analyses could be carried out in a more detailed way.
-	*RDL creation*	The Reference Data Library represents a repository of information, that must be maintained up to date for the whole duration of the project.

Table 8. Stage 3 edges.

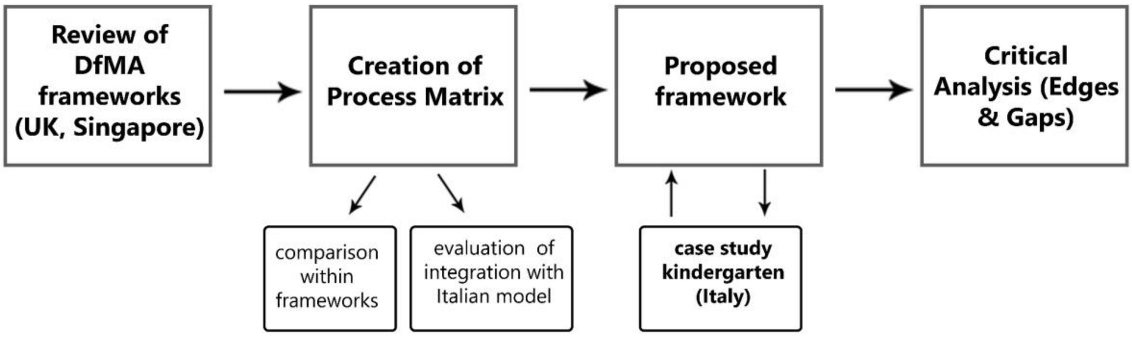
Main recipient(s)		Edges
-	*DfM and DfA*	The design of components is set to facilitate fabrication (manufacturing) and installation (assembling)
-	*??*	This system allows the production, preservation and analysis of a library of components, systems and products aggregates
	Multidisciplinarity	The created library can be shared and used to build a multi-sector platform

Table 9. Stage 4 edges.

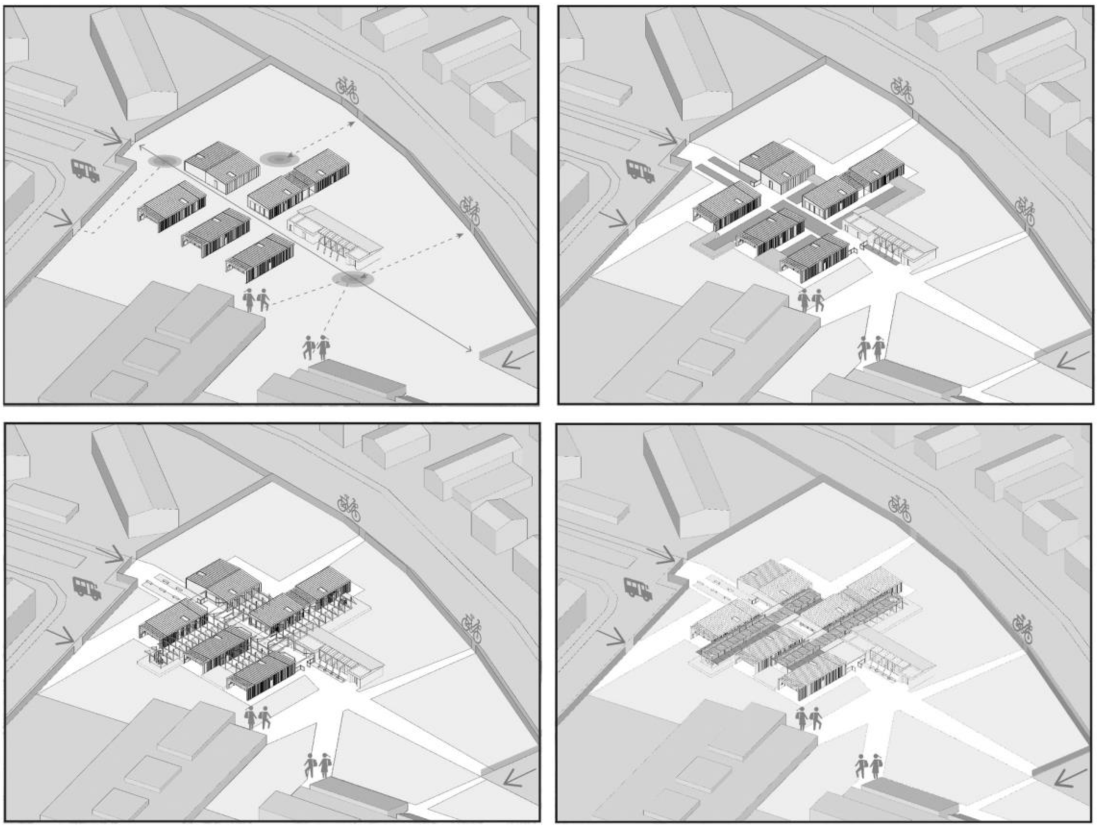
Main recipient(s)	Edges	
Manufacturers **Client**	*Integration*	Realisation of manufacture-ready drawings: the integration of disciplines provides a faster production process, avoiding misinterpretations
Client	*Factory environment*	The production of components (especially in case of complex ones) in a factory environment allows a better quality control.

Table 10. Stage 5 edges.

Main recipient(s)		Edges
Client Construction team	*Construction*	On-site activities will be limited to assembly, increasing speed, safety and quality of the building tasks. In addition, specialised labour need will be reduced.
Client	*Logistics*	To overcome logistic and transportation issues, it could be useful to move the factory near the building site, or to limit the evaluation of manufacturers to the ones working near the site.



RIBA	Singapore	Italy
Strategic definition	Project brief	Technical/economic feasibility
Preparation and brief	Concept design	
Concept design	Detailed design	Developed design
Developed design		
Technical design	Pre-construction	Technical design
Construction		
Handover	Post-completion	not defined
In use		



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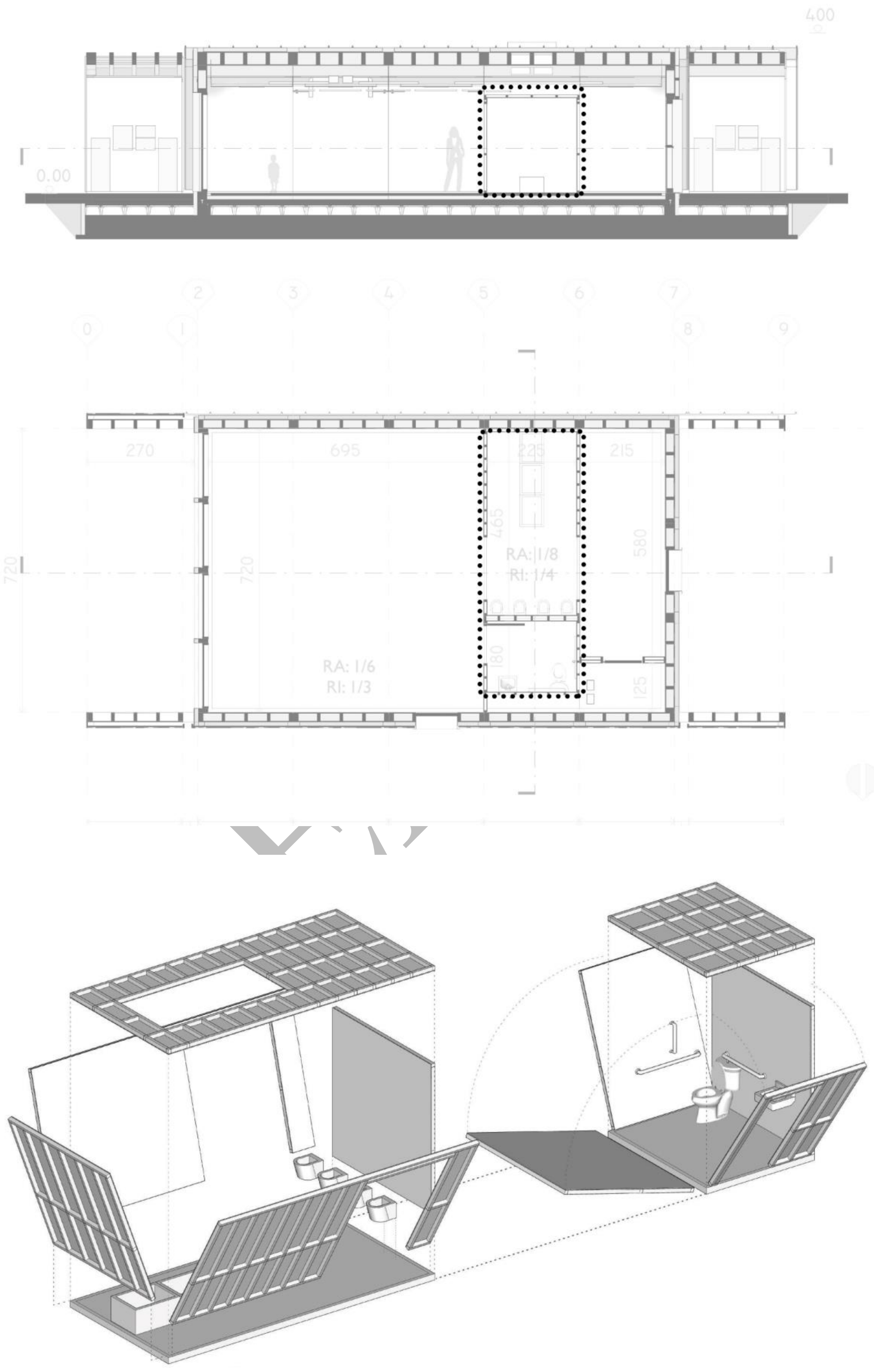

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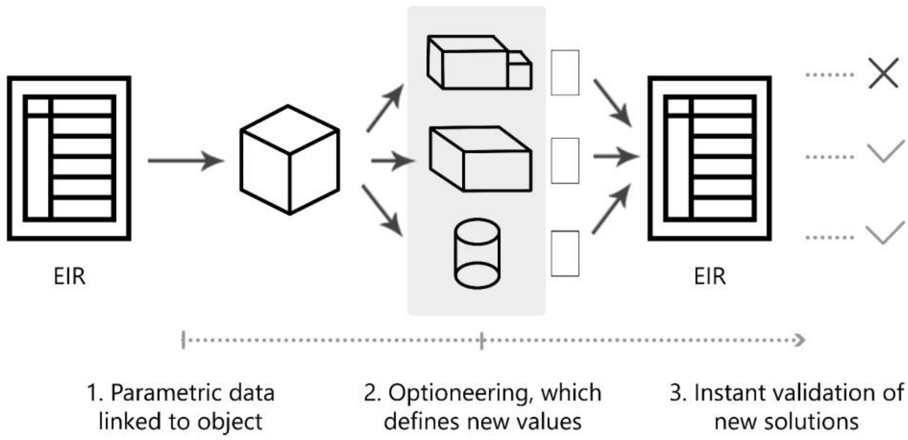

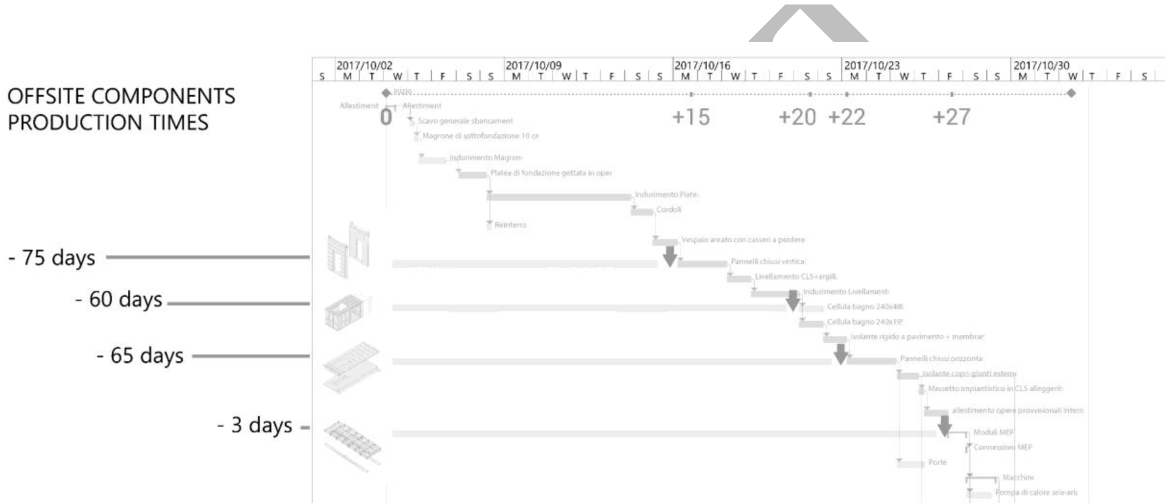

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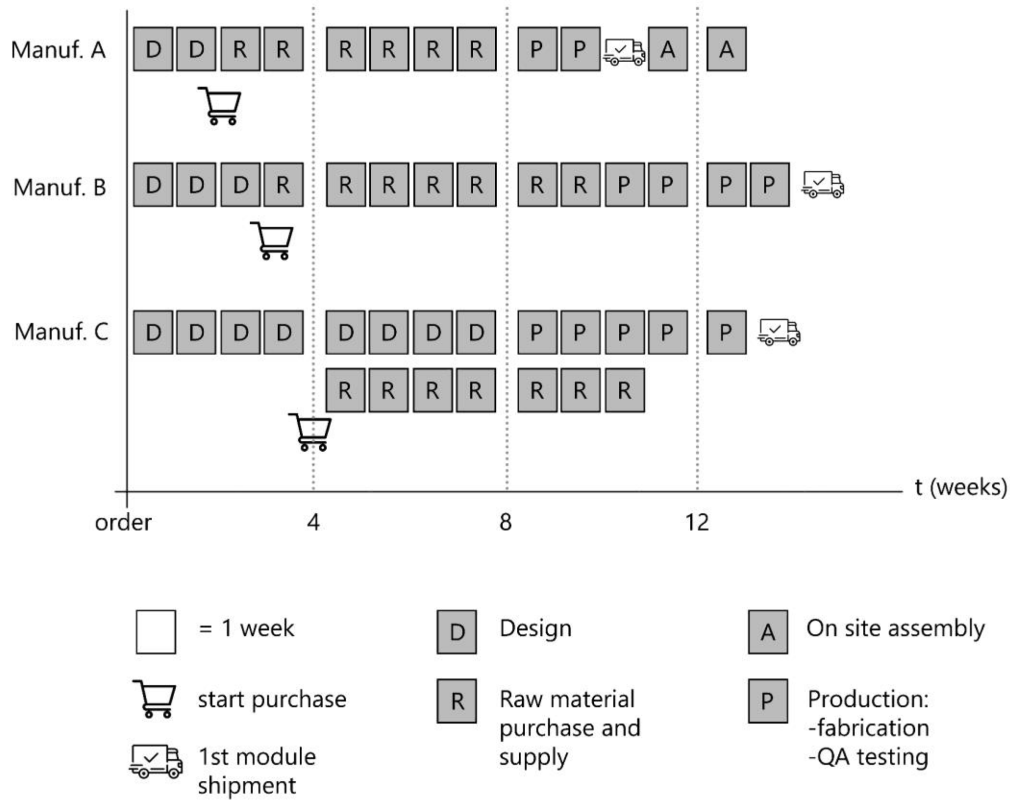

Figure 1. Methodology workflow diagram.

Figure 2. Project stages for UK, Singapore and Italy.

Figure 3. Case study building: kindergarten.

Figure 4. Bathroom pod in section (upper image) and plan (lower image).

Figure 5. Exploded view of the bathroom pod.

Figure 6. Concept Design Optioneering flow.

Figure 7. Manufacturing phases and times.

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Figure 8. Production times of off-site components.