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RESEARCH ARTICLE

The development of a design-for-assembly method for construction and infrastructure projects

Wim H. Verburg[1], Johannes I.M. Halman[1], Hans Voordijk[1]

[1] University of Twente, School of Engineering Technology, Department of Civil Engineering and Management, Enschede, The Netherlands

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Abstract

Building and infrastructure objects are no longer exclusively realized by processing materials at construction sites, but increasingly through on-site assembly of elements produced off-site. When designing an object whose realization is based on construction parts that are produced off-site, it is important to also consider the assembly of the components at the building location. Unfortunately, insufficient attention has been paid so far to interaction between the systems that are created through the realization of assembly processes. This inhibits achieving the full potential of using assembly processes. It manifests itself through issues such as dimensional deviations between the original design and the assembled system and also disappointing aesthetic results. These considerations have led to the general conclusion that the design and realization phases of construction processes are insufficiently aligned, and that more attention should be given in the design phase to the on-site assembly of the various construction parts. This article describes the development of a design-for-assembly methodology for construction and infrastructure projects. An initial version of this design-for-assembly method was applied in five construction projects and in one infrastructure project. Based on the results of the case studies conducted, further improvements were implemented leading to a final version of the design-for-assembly method. In addition, three validation workshops were organized involving thirty experts from the field of construction and infrastructure site management. A large majority of the experts concluded that the developed design-for-assembly method was a valuable addition to the design and realization process for building and infrastructure objects. Once these steps have been described, this article ends with a discussion on the scientific contributions made, the managerial implications, and offers directions for future research.

1. Introduction

Whereas traditional, stick-built construction involves bringing materials and skilled crafts and tradespeople to a site to construct a project, off-site construction methods such as prefabrication and modularization are playing a significant role and becoming more common [1]. These construction types can be realized as one-of-a-kind products, as part of a series, or as mass-produced objects. These off-site possibilities entail [2,3]:

Correspondence Johannes I.M. Halman j.i.m.halman@utwente.nl

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- Component manufacture and subassembly, examples include staircases and window frames;
- Volumetric preassembly, examples include sanitary facilities and modular elevator shafts;
- Non-volumetric preassembly, examples include façade elements and components of supporting structures;
- Modular building, examples include offices and residential blocks.

Undertaking the majority of the work in a controlled factory environment, before on-site assembly, reduces complexity and increases quality and productivity [4]. Barbosa et al. [5] and Bertram et al. [6] estimated that prefabrication and modularization have the potential to boost productivity between five and tenfold. Prefabricated parts can also provide greater safety, better quality, and lower rework rates since the manufacturing process allows more efficient and faster inspections and quality checks. The increased use of manufacturing technology and automation can also reduce human error and increase consistency. This can ensure that prefabricated parts and units arrive at the site in a condition that requires little remedial work before or during assembly, thus reducing build time [4]. However, despite the identified advantages of modularization and prefabrication, many projects still face construction time overruns, and some have even failed [7,8]. A major challenge in realizing modular and prefabricated constructions is the occurrence of dimensional and geometric variability [1]. When designing an object whose realization is based on the use of construction parts that are produced off-site, it is crucial to also consider the assembly of the construction parts at the building location. Unfortunately, insufficient attention has been paid so far to interaction between the systems that are created through the realization of assembly processes [9-12]. Although there are design and realization processes, these often do not tie together that well [13-16]. This gap between construction designs and their realization inhibits achieving the full potential of using assembly processes. It manifests itself through issues such as differences between dimensions in the original design and in the assembled system, disappointing aesthetic results, and construction times that are far longer than should be necessary. As a consequence, the potential increase in efficiency is not fully realized. This inability to fully achieve the potential efficiency also means that the use of construction parts produced off-site continues to have to compete with on-site production in the construction sector.

The above considerations have led to a general conclusion that the design and realization phases of construction processes are insufficiently aligned. In response, the main goal of this article is to contribute to the closing of the gap between the design and realization phases of objects in the built environment when created through an assembly process. This research goal has been met by developing an evidence-based design-for-assembly method for construction and infrastructure projects. An evidence-based design derives principles from research evidence and translates these into practices that solve construction problems [17,18]. This has been achieved through a rigorous systematic review [19] of a specific practice-related question:

How can construction and infrastructure objects be assembled using an evidence-based design-for-assembly method?

To close the identified gap between the design and realization phases of building and infrastructure objects, a design-for-assembly method has been developed that answers our main research question. The structure of the rest of this article is as follows. The next section provides a background of the literature that is considered relevant for this study. In Section 3 the research methodology and the successive steps that were followed to develop a design-for-assembly method for construction and infrastructure projects is explained. Subsequently, an extensive explanation of the developed method is provided in Section 4. Section 5 clarifies details of how the developed design-for-assembly method was justified and validated. Following this, in Section 6, the contributions to the literature, the managerial implications, and future research possibilities are discussed. Finally, the article ends with a summary of the main conclusions in Section 7.

2. Literature background

In the last few decades we have witnessed a considerable increase in the use of offsite methods of construction such as prefabrication and modularization [1]. Gibb [3] divides the off-site methods of construction into four categories, based on increasing amounts of pre-assembly:

- *Component Manufacture and sub-assembly*
  Many components used in construction are actually sub-assemblies (e.g. door furniture or light fittings). This category includes all small-scale sub-assemblies that would never be considered for on-site assembly in any developed country. Their use is outside the scope of this paper.
- *Non-volumetric pre-assembly*
  These items are assembled in a factory, or at least prior to being placed in their final position. They may include several sub-assemblies and constitute a significant part of the building or structure. Examples include wall panels, structural sections and pipework assemblies.
- *Volumetric pre-assembly*
  These items are also assembled in a factory. They differ from non-volumetric in that they enclose usable space and are usually installed on site within an independent structural frame. Examples include toilet pods, plant room units, pre- assembled building services risers and modular lift shafts.
- *Modular building*
  These items are similar to volumetric units, but in this case the units themselves form the building, as well as enclosing useable space. They may be clad externally on-site with ‘cosmetic’ brickwork as a secondary operation. Examples include out-of-town retail outlets (McDonald’s Drive-Thru), office blocks and motels (Forte, Friendly etc.) as well as concrete multi-storey modular units used for residential blocks in Korea (now also used for UK prison buildings).

The increase in the use of off-site methods of construction is due to numerous advantages which include shorter project schedules, lower costs, increased safety and improved quality control [1; 20-25]. However, a major challenge in the use of off-site methods of construction is the occurrence of dimensional and geometric variability [1]. Variability, which can be defined as the change in size and shape of features or parts is inevitable in both construction and manufacturing, which is why engineers often communicate allowable variations in terms of tolerances [22]. As explained by Shahtaheri et al. [1], factors influencing the need for tolerances in off-site construction include component variability, production process limitations, measurement imprecision, volumetric changes (i.e., thermal, shrinkage or creep strain), deformation from transportation and handling, or discrepancies between module interfaces. Tolerance management, in general, deals with analyzing and controlling the variability of dimensions and geometry, which is often achieved through the specification and control of tolerances. Although the term dimension in engineering can refer to any physical property that can be quantitatively measured, a dimension in construction typically refers to a linear or spatial measurement (e.g., length of a steel beam, or width, length, and height of a room, or distance between footings). With this in mind, designers use dimensional tolerances to communicate the amount of allowable variability of nominally defined dimensions [1]. The accumulating effects of dimensional and geometric variability in the use of off-site methods, have traditionally been managed using trial and error strategies and in the use of standardized tolerance values for similar stick-built construction scenarios. Unfortunately, this approach often leads to site-fit rework. To reduce this amount of site-fit rework, Thai et al. [8] conclude in their review of recent developments in off-site construction technologies, that one of the main challenges is still the lack of a reliable method for the design of the assembly of off-site produced building parts. This gap in literature has also been identified by Koskela [26], Yuan et al. [10], Gao et al. [11] and Yang et al. [12].

3. Research methodology

As explained in the introduction section, the objective of this research has been to develop a design-for-assembly method for the specific setting of construction and infrastructure projects.

To this end, we opted to apply the design science methodology proposed by Van Aken [27,28] and by Heusinkveld and Reijers [29].

The fundamental objective of design science research is to develop knowledge that can be used by professionals in the field in question to design solutions to their problems. The core product of design science research is a generic design. This generic design should be a well-understood and well-documented innovative design that has been field-tested to establish its pragmatic validity. The design science research methodology distinguishes five consecutive tasks or phases:

1. Analyzing the problem.
2. Developing the first draft of the construction assembly design method.
3. Testing and evaluating the first draft of the construction assembly design method.
4. Redesigning and finalizing the first draft of the design method and assessing its relevance and applicability.
5. Reflecting on the scientific and societal contributions of the research.

The application of these five phases will now be explained in more detail.

Phase 1: Problem analysis

Initially, time and effort was put into a preliminary phase to define the research objectives, conduct a literature review, as well as interviewing several experts in the field of construction and analyzing current developments in the construction sector such as building information modelling (BIM), new production technologies, and the latest measurement technologies.

Due to the paucity of relevant literature on design-for-assembly in the field of construction, an extensive literature study of applications in the mechanical engineering field was conducted [30-37]. Here, the purpose was to evaluate to what extent the construction sector could learn from the assembly practices used in mechanical engineering. It was evident from the literature study that designers of all types of assemblies are confronted with geometric variations as a result of production and assembly processes [3,38,39]. Further, it is not unreasonable to consider these geometric variations as the most fundamental problem to be solved in the process of designing assemblies.

The consulted experts in the construction field all considered it especially desirable to prevent or close the gap between the construction design and the realized buildings and infrastructure objects. They particularly emphasized practical issues related to geometric variations that may occur as a consequence of this gap:

- Dimensions in the assembled systems that deviate from the design;
- The design is not based on the dimensions of the components used in the assembly;
- The aesthetic result intended by the designers proves infeasible in practice;
- The specification of the systems to be realized is incomplete;
- Construction times are far longer than necessary.

In addition, it became clear that, compared to mechanical assemblies, the assembly of objects in the built environment faces additional challenges due to the fact that the assembly work is usually carried out outdoors and always at different locations. As a consequence, the assembly process is exposed to all sorts of weather conditions and different local contexts.

Our preliminary studies helped us to understand that the specific characteristics of the building industry require a design-for-assembly method that not only takes into account possible geometric variations, but also addresses variations in the contexts in which the assembly will be created.

Phase 2: Development of a draft design-for-assembly method

During this phase, an initial draft of the construction assembly design method was developed. Particular attention was not only given to design issues that are relevant for the design of assemblies in general but also to issues related to the specific requirements for designing objects assembled in the built environment. The design specification covered the following four assembly challenges:

- Objects in the built environment often consist of different types of components that are produced off-site [2, 40]. For example, a building may consist of a substructure (e.g. pile foundations); a primary structure (e.g. floors); secondary structures (e.g. walls and floor openings); finishes (e.g. external wall finishes); mechanical services (e.g. water supply); electrical services (e.g. lighting); and facilities (e.g. sanitary facilities). These construction parts mostly originate in different production systems. In designing the assembly of a building object, the object has to be seen as a collection of systems, a so-called system-of-systems [3]. The meeting points between systems are called system-to-system joints. The design-for-assembly method should give special attention to anticipating and solving potential problems that may occur with respect to these system-to-system joints.
- The assembly of the parts of a building or infrastructure object should result in the realization of the design intent, i.e. meeting the technical and aesthetic specifications. This requires a detailed description of the design intention.
- Built objects are connected to the ground through their foundations. Foundations may deform or move when assembling the construction parts on top of the foundation. Deformations may also occur over time. This requires a design-for-assembly method that makes use of available information on the expected deformation.
- The various construction parts are designed and manufactured by different suppliers in a distributed but collaborative environment. The alignment of the different construction parts must therefore be clearly represented in an assembly model which serves as an important element in mutual communication.

Phase 3: Testing and evaluating the first draft of the design-for-assembly method

During the third phase, the first draft of the developed design-for-assembly method was evaluated in a number of representative case studies in the Netherlands. These case studies involved the application of off-site fabrication and on-site assembly processes. Four large scale energy transformation projects in the residential sector, plus one office building project in the utility sector and one pedestrian bridge project in the civil engineering sector were selected as case studies.

As part of the energy transformation policy program in the Netherlands, four construction companies signed an agreement with the government to renovate 11,000 dwellings in a five-year period to such an extent that their total annual energy consumption, based on a number of given preconditions, would be zero. The realization of the program consisting of four energy transformation projects was based on the use of construction parts that were mass-produced off-site. This made the program consisting of four distinct transformation projects a relevant candidate for testing the first draft of the design-for-assembly method. In selecting the four transformation projects, attention was given to securing sufficient variation among these not dissimilar types of cases. The transformation projects differed in terms of their desired functionality, the size of the series, and the applied systems of construction parts produced off-site.

A primary condition in the process of selecting an adequate office building as case study, has been that the product architecture had to be based on the use of structural parts that are produced offsite. With the exception of its foundations, this holds for the selected office building case. The office building case can be considered as a one-of-a-kind object.

Many Dutch cities are characterized by their canals. To cross these, one needs bridges. The pedestrian bridge project that was selected as a case study for testing and evaluating the first draft of the design-for-assembly method, pertains to a set of fixed bridges for light traffic. The city of Rotterdam was facing the challenge of replacing 35 of such bridges. With the exception of the foundation, these bridges will be based on the use of construction parts that are produced off-site. The pedestrian bridge case study focused on the extent to which the design-for-assembly approach could be used in replacing these type of bridges throughout the Netherlands on a large scale. The materials that were used in the six case studies are mainly concrete, fiber-reinforced plastic, steel and wood. The fiber-reinforced plastic is used for volumetric pre-assembly, the other materials as component manufacture or non-volumetric pre-assembly. Together, the case studies can be considered representative of assemblies of systems that might be applied in the development of objects for the built environment in the Netherlands.

The realization of the selected objects was monitored by closely observing their on-site assembly processes. The monitoring covered the following processing steps:

- Attaching the hoisting facility
- Transporting a construction part to the assembly position
- Positioning the construction part
- Providing stability during assembly
- Detaching the hoisting facility
- Attaching the construction part
- Finishing
- Verifying the quality

In order to test the first draft of the design-for-assembly method, it was verified to what extent: (1) the assembly was carried out in accordance with the design-for-assembly prescriptions; (2) the construction part was processed on site for the purposes of the assembly; (3) the cycle times of the assembly of similar construction parts differed; (4) the intended quality was realized. Based on the results and evaluation of the conducted case studies, the first draft of the design-for-assembly method was further refined and worked out in more detail.

The changes that were made concern details in the description of the successive steps in the design-for-assembly method. The demand specification step did not pay attention yet to the possible relevance of designing a product typology if the assignment relates to a number of objects with a comparable function (as is the case in the pedestrian bridge project).

For the spatial and functional design step it was noticed, that attention should also be paid to the product architecture of the assembly, by avoiding too many systems and a fragmented assembly of systems.

The system design step proved its relevance in all case studies. For an efficient assembly, the availability of the systems to be assembled, the continuity of the assembled processes, the robustness of the systems to be assembled and the feasibility of the system-to-system joinings should be considered.

Likewise the evaluation made clear that the nominal design step design also needs to consider the process of positioning the construction parts using cranes: the space taken up by hoisting straps, slings, end plates, foot plates, bolt shanks and existing pipelines must not be overlooked.

The variation design step needs to focus on the deformations that may occur during assembly. This is because it is often impossible to assemble a deformed construction part in a controlled manner. Furthermore, it is desirable to assess the availability of the hoisting paths that will be required during the assembly.

For the preparation of the assembly step the evaluation made clear that there should be a focus on preparation at the system level, rather than at the construction part level. For each system to be assembled, its position in relation to a geodetic datum should be recorded. Parallel dimensioning should be used in assembly plans for the realization of an assembly. Further, one should ensure that the assemblers have the requisite experience and also conduct a test assembly if there is any doubt. This should not be left until the first few cycles of an assembly process since these are inappropriate for this purpose.

Finally, the evaluation of the first draft learned that ensuring the quality of the assembly of systems needs explicit attention. When designing the assemblies, it should always be possible to safeguard the quality achieved during assembly.

Consequently, the necessary activities should be incorporated in the design.

Phase 4: Redesigning the first draft of the design method and its relevance and applicability

Based on the results and evaluation of the conducted case studies, the required modifications were implemented leading to a final version of the design-for-assembly method which is presented in Section 4 of this article. To validate the practical relevance and applicability of the developed design-for-assembly method, three workshops with experts in the field of construction and infrastructure site management were organized. The workshops covered the relevance and applicability of the developed method for the residential building sector, the non-residential building sector, and for infrastructure projects respectively. To gather feedback, the experts participating in the workshops were asked to complete a questionnaire and to elaborate on the developed design-for-assembly method. Further, the experts in the workshops were asked if they felt some modifications were still necessary. The findings of this validation process are presented in Section 5.

Phase 5: Reflection on the scientific and societal contributions of this research

In this phase the added value of the developed design-for-assembly method was evaluated by assessing its relative contribution to the body of knowledge, its value in the practice of assembling building parts and by considering its limitations.

4. The final version of the design-for-assembly method

The final version of the design-for-assembly method consists of eight sequential steps (see also Table 1 for the sub-steps). These steps are:

1. Design of the typology.
2. Determining framework conditions.
3. Selection of the product architecture.
4. Design of the system-of-systems assembly.
5. Nominal design of the assembly.
6. Assessment of the feasibility of the assembly.
7. Preparation and execution of the assembly.
8. Completion of the assembly.

Step 1: Designing the typology

A typology represents the compositions of the various systems to be produced off-site with which the new object can be put together. This can be represented using a morphological map [41]. For projects that involve the integration of objects in several contexts, a typology can be developed by combining the characteristics of the contexts and the systems to be produced off-site with which these objects will be assembled.

Step 2: Determining the framework conditions

Based on the demand specification, the performance aspects that need to be realized in terms of the planning and associated preconditions can be determined for the assembly design. This can be done concurrently with the development by third parties of the principle solution for the object to be realized. In order to assess the applicability of the assembly approach for the building or infrastructure object in question, the on-site logistical situation and the possible supply routes for construction parts that are produced off-site need to be described. This will reveal the maximum dimensions that will allow parts to be brought in from off-site and manipulated at the assembly location in order to realize the assembly. To gain insight into the physical load-bearing capacity of the construction site, information is required about the soil conditions and the possible availability of hard surfaces. It is then possible to determine what hoisting facilities and auxiliary structures can be utilized. It is essential to take account of possible long periods of rain leading to soft ground.

Step 3: Selecting the product architecture

Based on the principle solution (step 1) and the modular or integrated approaches selected for similar objects (step 2), the product architecture options to be used can be identified and described. It is also advisable to consult other sectors, such as shipbuilding or the offshore industry, since this may bring fresh insights with regard to the assembly possibilities. By confronting the possibilities with the framework conditions, potentially promising options can be identified.

Table 1. Steps in the building process and the Design-for-Assembly method

Building process steps		*Design-for-Assembly method: Main steps*	*Design-for-Assembly method: Sub-steps*
Feasibility study	1.	Designing the typology	▪ Define the characteristics of the context ▪ Define the functionality of the off-site systems to be produced and possible versions thereof ▪ Identify combinations of the context-related characteristics and the possible versions of the off-site produced systems
Project definition	2.	Determining the framework conditions	▪ Describe the achievable performance and preconditions
Structure design	3.	Selecting the product architecture	▪ Generate modules to be produced off-site and/or systems of potential, promising options for the product architecture ▪ Determine the promising options for this (the product architecture) using value analysis ▪ Select a promising option
	4.	Designing the system-of-systems assembly	▪ Break the concept design down into elements ▪ Gather information for the systems' templates ▪ Establish preferred dimensions, sequencing, and delineation ▪ Optimize the sequencing ▪ Define system-to-system connections ▪ Assess feasibility of the assembly
Preliminary design	5.	Determining nominal design of the assembly	▪ Quantitatively describe the key characteristics to be realized in the as-built situation ▪ Determine the critical points and the position of the components in the as-built situation ▪ Determine the nominal dimensions of the components ▪ Design the system-to-system interfaces ▪ Describe the quality control to be carried out in the as-built situation
Final design	6.	Assessing the feasibility of the assembly	▪ Assess the geometric position of all the assembled parts ▪ Assess the design of the interfaces ▪ Assess the realization of the system-to-system connections ▪ Assess the time required to realize the assembly ▪ Assess the tolerances in the system-to- system joints
Job description (bill of materials) Pricing Work preparation			
Realization of the object	7.	Finalizing the built assembly	▪ Draw up an assembly plan for each system to be assembled ▪ Realize the assembly of the systems
Delivery of the object	8.	Handing over the built assembly	▪ Handover of the quality checks carried out during the assembly of the individual systems to the client

A value analysis conducted by a cost engineer (i.e., value engineering) can be helpful in the process of selecting the most promising options for the principle solution by identifying the most economic product architecture. If there are no promising options, an alternative principle solution (repeat of step 1) must be developed.

The design result consists of the concept design, the most promising options for the product architecture, the possible assembly processes, and the framework conditions. An object breakdown structure can be used to describe the product architecture options. The concept design should also provide information regarding the aesthetics of the joints between parts. These can be represented more accurately using principle details. Based on the choice of the product architecture, suppliers, with or without the involvement of a system integrator, can continue to work on the design and the realization of the assembly.

Step 4: Designing the system-to-systems assembly

Based on the chosen product architecture and the concept design the following six topics are covered in the system-to-system assembly design.

1. Breaking down the concept design

The first step consists of breaking down the concept design into systems for off-site production. Given that the concept design is based on a promising product architecture option, such a breakdown should be possible. Provided the breakdown results in functionally described systems, these then have to be realized. For example, in the utility building project case, this is reflected in the choice of a steel framework as the supporting structure.

2. Gathering information for the systems' templates

To produce the system-of-systems design, it is essential to have information about the various systems that are described in the break down. In line with the "assembly-oriented design" approach used in designing industrial products, so-called system templates can be drawn up for these systems [[34]]. This process integrates the design of the product and the design of the assembly. As such, a template must contain all the information relevant to the assembly.

Creating a construction system template is seen as a way to gather all the information required for the application of a construction system that is produced off-site. Since this is not object-related, it is possible to draw on past experiences with a system and provide insights into the extent to which information is, or should be, available on a system. If the desired information is missing, this can be seen as a warning with regard to the controllability of the assembly process. Ideally, a construction system template should address the following aspects: assembly process, geometry and tolerances, interfaces, delivery times and quantities and onsite provisions.

3. Preferred dimensions, sequencing, and delineation

The assembly processes for construction systems may be based on certain dimensions of the parts to be assembled. This aspect should be described in the template. While determining the sequencing, it will become clear in what order the assembly can be realized. The system limits are clarified by indicating or describing the delineation between systems. This is particularly relevant when it comes to realizing the system-to-system joints and interfaces. The sequencing drawn up during this design phase is intended as a starting point for its optimization. Fragmented assembly processes should be avoided.

4. Optimizing the sequencing

In the assembly of most construction systems, cranes and assembly teams with certain competences are utilized. Given that their deployment is costly, it is desirable to carry out assemblies in a sequential manner that avoids waiting times. In addition, it is desirable to avoid having to realize small specialized assemblies using specially trained teams. To this end, it is advisable to simulate such assemblies in a stylized manner on paper. The information from the template, the preferred dimensions of the construction parts, the delineation and the sequential order that was drawn up earlier can all be utilized for this. This sequential order can be represented using the Design Structure Matrix [33,34,42,43].

5. System-to-system connections

After deciding on the assembly order, the system-to-system connections can be inventoried and the desired locations of the interfaces determined. Based on this inventory, the number of system-to-system connections can be optimized. Here, the saying "less is more" usually applies. In order to realize a system-to-system connection, the location of an interface must be such that the part to be added can be moved, with a crane if necessary, into the desired position based on the associated assembly process. The weight of parts often makes it impossible to manually move them horizontally during the positioning process. The location of the interfaces must therefore be designed to avoid the horizontal movement of heavy parts when positioning them. This also facilitates the application of forced positioning. The desired functionality of the interfaces can be described in terms of the design. With this information, it is then possible to qualitatively describe the quality of the assembly base to which this interface is attached.

6. Feasibility of the assembly

With the information that is now available on the system-to-system level, the individual systems, including their limits in relation to the location of the connection of an interface or joint, can be qualitatively represented. After this, it can be assumed that the parts in question will be present at the assembly location and that they can be placed in the desired positions. Using this representation, it is then possible to determine whether the chosen systems are also compatible with the specified system-to-system joints. Systems are compatible if the key characteristics at the locations of the system-to-system joints can be achieved. Suitable suppliers can also provide validated quantitative information about an assembly that is represented by a certain flow-down.

Step 5: Determining the nominal design of the assembly

The input for the nominal design phase consists of the framework conditions, the concept design, the construction system templates, the system-to-systems design, and design information about the dimensioning of the individual systems.

The nominal design for the assembly of a system starts with a quantitative description of the key characteristics that have to be realized at the system and at the part levels, as well as those at the locations of the system-to-system joints. Next, the required position of these components in the as-built situation must be determined, along with the so-called critical points that can be used to position these components. Based on this information, and the dimensioning of the system parts, the nominal dimensions of all the parts can be determined.

In order to be able to attach the parts using the interfaces, the locations of these interfaces are then determined. In order to determine the room for adjustment at the interfaces, information about the assembly's key characteristics at the locations of the interface mountings is required. This information can generally be derived from the available construction system templates. Since a system design may no longer be fully in line with the template that was used previously, it is desirable to first determine whether the templates still match the design. If this is not the case, the templates in question need to be replaced with updated versions since it is not possible to design the assembly of a construction system without accurate templates.

Since assembly is only possible when the systems to be assembled meet the specifications, it is necessary to verify the geometric quality of an assembled system. In other words, the realization of the key characteristics have to be verified.

The nominal design can be represented three-dimensionally in a building information model. The information that is relevant for the assembly, such as the construction system templates, can be linked as non-graphical information to parts.

Step 6: Assessing the feasibility

Assessing the feasibility of the assembly's nominal design involves determining to what extent the key characteristics of the systems can be realized based on the nominal design. The deformations that occur over time and all potential sources of geometric variations that affect the object's key characteristics need to be taken into account. A simulation is conducted in the time domain to determine the geometric positioning of the assembled systems. The simulation can be pragmatically conducted by combining deformations of the structure over time with the positional deviations that occur as a result of the assembly process. The simulation needs to provide information on the geometric effects of deformations and all sources of geometric variations at the locations of the interface attachments. During the simulation, the following five aspects need to be assessed: geometric position of all the assembled parts, design of the interfaces, system-to-system connections, required realization time for the entire assembly, and the tolerances in parts at the system-to-system joints.

Step 7: Preparing for and executing the assembly

During the series of case studies, it became clear that the following aspects need specific attention during the preparation and execution of the assembly design:

- The robustness of the assembly designs;
- The occupational health and safety plan;
- The choice between simultaneous or consecutive realization of assemblies;
- The manufacture of construction parts;
- The transfer of design information to the realization phase;
- The availability of a local three-dimensional axis system;
- Information regarding the positioning of parts;
- The coordination between the supplier chain and the realization of the assembly;
- The safeguarding of the quality of the individual assemblies;
- The realization of the safety provisions;
- The coordination of facilities that extend beyond individual assemblies;
- The dimensioning, which should be based on parallel dimensioning.

Step 8: Completing the assembly

Completion takes place based on the provision of reports detailing the realized key characteristics of the assembly. The structure of such reports should be specified as part of the construction system templates.

5. Justification and validation of the developed design-for-assembly method

In this section, the developed design-for-assembly method is evaluated from two perspectives. First, we describe the precautions that have been taken to ensure that the necessary decisions can be deliberately taken in the design phase of a building or infrastructure project to ensure that an aesthetically satisfactory assembly can be efficiently realized. Second, we have verified to what extent the method is considered by industry practitioners to be appropriate and of adding value when adopted and applied to real-life construction projects.

Precautions taken to ensure an efficient and aesthetically satisfactory assembly

The essential first steps in the design-for-assembly method are the selection of the product architecture (step 3), the design of the system-to-system assemblies and the collection of the associated information on the systems to be used: i.e., the creation of the construction system templates (step 4). Based on the chosen product architecture and the construction system templates, the nominal design can be drawn up (step 5) where the aesthetic principles and the required performance are determined. In step 6, the feasibility of the object design is tested on the basis of the construction system templates and a list of requirements. If the design turns out not to be feasible, then either the design, the requirements, or the assembly processes need to be modified. Changing the requirements often reduces the value created, and adjusting the design or the assembly processes is associated with additional costs.

The construction time for the object to be realized is also a design aspect in the system-to-systems phase (step 4). Based on the information in the construction system templates, the construction time of the object can be determined and further optimized with the help of a Design Structure

Matrix [29,38,39]. A final assessment of the construction time takes place in step 6 and, after completing this step, all the design information for the assembly system is then available. The assembly plans for the systems to be separately assembled can then be established and carried out (step 7).

The adoptability of the developed design-for-assembly method

In order to determine the adoptability in practice of the developed design-for-assembly method, three three-hour expert workshops were organized. In total thirty experts participated in these three workshops. Each workshop had a different focus. The focus of the first workshop was on assembly in the residential construction sector, the second workshop on assembly in the non-residential construction sector, and the third discussed the assembly of infrastructural projects. The experts in the first workshop on assembly in the residential sector included three professionals working as developers in home contractor firms, three professionals working in architecture design offices, one expert from a construction consultancy company, one supplier of insulated structural panels for walls and roofs and two academic researchers in the field of industrialization in the residential sector. The experts in the second workshop on assembly in the non-residential construction sector consisted of two professionals working in architecture design offices, one representative from the concrete industry branch, and one representative from the façade industry branch and two academic experts in the field of industrialization in the construction sector. The experts in the third workshop on the assembly of infrastructure projects included two professionals working as contractors for infrastructure projects, one working in infrastructure design office, three producers of prefabricated concrete, two working as public clients of infrastructure projects, one as a supplier of fiber-reinforced polymer bridges, two experts working at engineering offices and two academic researchers in the field of civil engineering and management. During the workshops, the experts were first informed, through an oral presentation that included practical examples, about the substance and process steps of the developed design-for-assembly method. The presentation for each workshop was tailored to its specific focus. During and after each presentation, questions from the experts about the method were answered. This clarification and answering of questions was followed by an open discussion about the added value of the proposed design method. Finally, the experts were asked to complete a questionnaire to evaluate the developed design-for-assembly method. The experts were also asked to indicate if they felt there were any aspects that required modification and/or further clarification. In addition to this written qualitative evaluation, the experts were also asked to provide a score based on the statement: “The proposed design-for-assembly method can be meaningfully applied”.

The overall evaluation scores for the applicability of the construction assembly design method are shown in Table 2. Based on the validation workshops, it was concluded that a large majority of the experts recognized the added value of the developed design-for-assembly method and believed that the construction assembly design method could be applied in a meaningful manner in the construction process for residential, non-residential, and infrastructure building projects.

Table 2. The overall evaluation scores from the three workshops on the applicability of the construction assembly design method in practice.

Evaluation criteria	Scores on the statement: The proposed design-for-assembly method can be meaningfully applied	
	In numbers (n=23)	In percentages
Totally disagree	1	4%
Mostly disagree	1	4%
Neither agree nor agree	3	13%
Mostly agree	11	47%
Totally agree	7	30%

6. Discussion

Scientific contributions

Our built environment is no longer primarily realized through processing materials at construction sites, but mostly by putting together, on site, elements produced elsewhere. When designing an object whose realization is to be based on the use of construction parts that are produced off-site, it is important to also consider the design for the assembly of the construction parts at the building location. The design of this assembly and its connections with other construction parts that are to be similarly included, have a major impact on the efficiency of the realization process. As explained in the introduction section and in literature review section, insufficient attention has been paid so far to the interaction between the systems that are created through the realization of assembly processes. [9-12]. Design and realization processes often do not tie together that well. This gap between construction designs and their realization inhibits achieving the full potential of using assembly processes. Several scholars [9-12, 23] have identified the lack of a reliable method for the design of the assembly of off-site produced building parts as an important gap in the construction management literature.

Due to the paucity of relevant literature on design-for-assembly in the field of construction, an extensive literature study into the design of mechanical assemblies was conducted. This in-depth literature review revealed that designers of all types of assemblies are confronted with geometric variations as a result of assembly and production processes. The existence of these geometric variations can be considered as the most fundamental practical problem to be solved in the design and realization of assemblies. Second, and the most important scientific contribution of this article, is the development, application, and validation of a design-for-assembly method that can be applied in the process of designing and executing construction and infrastructure projects. This method takes into account geometric variations that occur as a result of assembly and realization processes in construction and infrastructure projects and identifies appropriate solutions for the four assembly challenges explained in section 3 of this paper. This design-for-assembly method can not only be considered as a valuable complement to the existing literature on construction and infrastructure management but also as potentially contributing to existing international building standards. Currently, the ISO building standards [44] include documents related to Structures; Building materials and products; Energy performance and sustainability; Fire safety and firefighting; Concrete and cement; Timber; Masonry; Information management in construction; Heating, cooling, and lighting; Lifts and elevators; and Design life, durability, and service life planning, but do not yet include standards addressing alignment between design, production, and assembly processes. The design-for-assembly method as described in this article can contribute as one of the first steps in developing international building standards on the alignment of the design, production, and assembly of buildings and infrastructure objects.

Managerial implications

The design-for-assembly method described in this article can be used for the design optimization and realization of an assembled object in the built environment, and in both renovation and new construction projects. Its applicability is particularly relevant for those parties who are regularly responsible for, or have a stake in, the efficient realization of objects in the built environment and that have a product architecture that is based on the assembly of construction parts produced off-site. Applying the developed design-for-assembly method could contribute to a more efficient assembly and production process, improved worker safety, and a decrease in avoidable construction waste. By applying the design-for-assembly method, on-site activities can be more often limited to assembling by avoiding the need for additional unforeseen on-site work. This will reduce the often labor-intensive on-site processing of building materials. In addition, applying the design-for-assembly method will stimulate the take-up of product architectures that are based on the on-site assembly of off-site produced modular construction parts. These two developments will lead to a more efficient production process and thereby raise labor productivity in the construction and infrastructure sector.

Recent research by the Royal Institute of British Architects [45] and also by Tam et al. [46], Li et al. [47], Li et al. [48], Thai et al. [8] and Lu et al. [49] has shown that off-site production has the potential to contribute to better quality, faster construction, less resource consumption, reduced on-site waste, and better environmental performance than traditional ways of construction. However, as we explained in the introduction section, a major challenge is still to accommodate the dimensional and geometric variations that occur. The developed design-for-assembly method could contribute to overcoming this challenge. This will reduce the need for improvisation in realizing assemblies and the consequent risk of accidents on the construction site.

Recommendations for further research

The development of the design-for-assembly method as described in this article has raised questions that would benefit from further research.

First, although several case studies have been conducted to evaluate the added value of the developed design-for-assembly method, these evaluations have focused on renovation projects in the residential sector, on the design and realization of an office-building project, and on a pedestrian bridge project in the civil engineering sector. These evaluations have contributed to improvements to the initial version of the design-for-assembly method. Further improvements and extensions could be expected from additional case studies in the field of new-build residential dwellings, other types of utility buildings, and other types of infrastructure projects such as viaducts and road bridges.

Second, all the case studies reported in this article have been conducted in the Netherlands. Therefore, further evaluation studies are recommended outside the Netherlands to investigate whether there are specific conditions that warrant extra attention or refinement for the successful and wider application of the developed design-for-assembly method. This would clarify and improve the generalizability of the proposed method.

7. Conclusions

A major challenge in the realization of modular and prefabricated construction projects relates to the occurrence of dimensional and geometric variability. Failures in the design phase of a construction project to anticipate the potential geometric changes that may occur to modules and other building parts may lead to on-site reworking, longer lead times, cost overruns, and aesthetically disappointing results. The design-for-assembly method proposed in this article can be considered as a valuable tool to ensure that deliberated decisions are taken in the design phase to realize a design through which an efficient and aesthetically satisfactory assembly can be achieved.

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Author Contributions

W.H. Verburg: Conceptualization, Methodology, Validation, Investigation, Data Curation, Writing Original Draft; J.I.M. Halman: Conceptualization, Methodology, Writing-second Draft and Editing, Supervision; H. Voordijk: Conceptualization, Methodology, Writing-Review and Editing, Supervision.

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Data Availability Statement

The data presented in this study are available on request from the corresponding author.

Ethics Committee Permission

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Conflict of Interests

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