

The adoption of green modular innovations in the Dutch housebuilding sector

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ARTICLE INFO

Handling editor: Cecilia Maria Villas Bôas de Almeida

Keywords:
Green innovation
Adoption
Modularity
Housing projects

ABSTRACT

This article reports on an in-depth multiple case study into the adoption of green modular innovations in the housebuilding sector. This adoption of green modular innovations is important because it enables a substantial improvement in terms of sustainable building. For this study, three modular innovations were selected – a modular renewable energy system, a modular bathroom pod and a modular photovoltaic roof. The multiple case study helped to identify ten variables that influence the adoption of these modular innovations. A closer analysis also revealed interrelations between several of the identified variables. Based on this analysis, four paths leading to the potential adoption of green modular innovations were identified. For each path, propositions were developed. These paths enable one to explain how and why green modular housing innovations are adopted. From these findings we derived clear managerial and policy implications while future research directions are also addressed.

1. Introduction

Reducing energy consumption and CO₂ emissions are increasingly important cornerstones of sustainable policy development for governments and industry around the world to address grand societal challenges related to sustainability, climate change and energy security. In line with the EU's commitment to global climate action under the Paris Agreement, the EU expressed its goal to be climate-neutral by 2050 in the 'European Green Deal' (EU, 2019, 2020a). To be able to reach this goal, one needs to understand the barriers that hamper the uptake of relevant innovations in various domains. The focus of this study is the built environment and, more specifically, house building (ECSSO, 2018a; EU, 2020b; Eurostat, 2019a). Housebuilding contributes to about 40 % of total CO₂ emissions globally, with 27 % of energy consumption taking place in residential buildings. To substantially increase operational energy efficiency, an enormous effort will be necessary in the coming years to upgrade the existing and future housing stock (Arnoldussen et al., 2017). For this reason, various governmental programmes have been initiated to facilitate the transition towards zero energy (ECSSO, 2018a, b; EU, 2020c), circular (Ellen MacArthur Foundation, 2015a, b) and industrialized (Barbosa et al., 2017; Bertram et al., 2019; Ribeirinho et al., 2020) housebuilding to improve both the efficiency and the

quality of housing. As such, the housebuilding industry will need to align sustainability and productivity by maximizing sustainable productivity through realizing green innovations (Aldieri et al., 2019). Following Tello and Yoon (2008), green innovation can be defined as (p.165): "The development of new products, processes, services and technologies that contribute to the development and well-being of human needs and institutions while respecting natural resources and regeneration capacities". Green innovations are more complex than other types of innovation for various reasons (Messeni Petruzzelli et al., 2011). Green innovations require more complex and diversified knowledge and skills, that is, they tend to require a systemic combination of technologies sourced from multiple stakeholders across various industries (Authority and Allé, 2012; Horbach et al., 2013; Nemet, 2012). Therefore, knowledge spillovers and multidisciplinary, inter-organizational cooperation are considered key to the development and subsequent adoption of green innovations. Both aspects have recently seen growing attention in green innovation research (e.g., Messeni Petruzzelli et al., 2011; Ardito et al., 2016, 2019b,a; Cillo et al., 2019).

Modular construction principles can be considered a key strategy in developing green innovations and realizing a transition towards a smart, industrialized, sustainable and eventually circular housebuilding sector. Modular product systems involve one-to-one mapping between

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<https://doi.org/10.1016/j.jclepro.2021.128524>

Received 9 May 2020; Received in revised form 13 July 2021; Accepted 2 August 2021

Available online 3 August 2021

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functions and physical subsystems and have standardized, decoupled interfaces that allow subsystems to be combined in different ways to configure product variants (Salvador, 2007; Ulrich, 1995). As already showcased in various other industries (Chung et al., 2014; Kimura et al., 2001; Ma and Kremer, 2016; Okudan Kremer et al., 2013), modularity if applied in housebuilding has the potential to ease the disassembly of buildings into their constituent components providing opportunities for the re-use of components and the refurbishment and recycling of components that are at the end of their life (Ellen MacArthur Foundation, 2015a, b; Van den Berg, 2019). Given that building modules can be produced offsite in factories, and can easily be fitted together on site using standardized interface designs, this approach provides better controlled conditions to produce more efficiently and with less waste than traditional, on-site production techniques. Modular building designs also enable the independent design and (re-)use of subsystems at the cross-project level allowing economies of both scale and scope in production and design processes (Baldwin and Clark, 2000; Halman et al., 2008; Veenstra et al., 2006). On top of these gains, the mixing and matching of product modules will allow housebuilders to offer individualized housing solutions while retaining the advantages of economies of scale linked to mass production (Barbosa et al., 2017; Bertram et al., 2019; Naim and Barlow, 2003; Ribeirinho et al., 2020). As such, modularity creates an opportunity for housebuilders to more efficiently meet a much larger range of customer requirements, and at the same time improve sustainability and productivity in the housebuilding sector.

Despite the coercive pressure from policies to reduce the environmental impact of housebuilding, the housebuilding industry has still not widely adopted green modular-based innovations and the industry seems to be at an impasse (Barbosa et al., 2017; Bertram et al., 2019). Little attention has been devoted in the literature to the factors and mechanisms that determine the potential adoption of green modular innovations in the housebuilding sector. Cillo et al. (2019) identified a lack of empirical evidence about factors enabling or hindering sustainable building practices as an important gap in literature. In order to fill this gap in the literature, we address the following two research questions in this paper:

- 1) What determining factors and mechanisms influence the adoption of green modular innovations in the housebuilding sector?
- 2) To what extent can the theory on modularity help to explain the adoption, or failure, of green modular innovations in the housebuilding sector?

These research questions have been addressed through a multiple case study conducted in the Netherlands investigating the adoption of three green modular innovations. Three case studies address a modular renewable energy system, a modular prefabricated bathroom pod and a modular photovoltaic (BIPV) integrated roof system.

The remainder of this article is structured as follows. Section 2 reviews the literature on modular innovation and its adoption both in general and more specifically in the housebuilding sector. Next, in Section 3, we explain the research methodology. Section 4 describes the findings from the three independent case studies, the cross-case analysis and the developed propositions. The article concludes with a discussion on the main contributions, policy implications, limitations of this study and a number of suggestions for further research.

2. Background literature

In Subsection 2.1, we first provide a general discussion on the Dutch housebuilding sector - the market in which the green modular innovations included in this research are introduced. This is followed by a general introduction to the concept of modularity in Subsection 2.2 where we distinguish three dimensions of modularity as described by Fine et al. (2005), Elram et al. (2007) and Campagnolo and Camuffo

(2010). We continue our review with a discussion on modularity in the housebuilding sector in Subsection 2.3. Here, a three-dimensional modularity typology for modular housing projects is derived based on the available literature. Finally, Subsection 2.4 provides an overview of the research findings on the adoption of innovation in housing projects and, more specifically, the adoption of modular innovations in housing projects.

2.1. Background of the Dutch housebuilding sector

The total Dutch housing stock consists of some 7.8 million homes (BZK, 2019; Faessen et al., 2017). About 5 million of these are single family households and about 2.8 million are homes in multi-family buildings. The housing market can be segmented into social housing, commercial real estate and privately-owned housing, with roughly 2.3 million, 1.1 million and 4.4 million homes respectively.

A sharp increase in housing demand as a result of various demographic developments and a substantial decline in house building since the credit crisis (2007–2011) has led to a considerable housing shortage in the Netherlands. To close this gap, the Dutch government determined, in its National Housing Agenda (BZK, 2018a, b), to build 75,000 homes per year over the next decade. However, substantial job losses after the credit crisis led to a decline in production capacity. Consequently, this pressing and immediate need for increased housing production can only be achieved through a significant increase in industrialization. Undertaking the majority of the work in a controlled factory environment, before on-site assembly, reduces complexity and increases quality and productivity. Barbosa et al. (2017) and Bertram et al. (2019) estimated that prefabrication and modularization have the potential to boost productivity between five and tenfold. Prefabricated parts can also offer higher 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 on site in a condition that requires little remedial work before or during assembly, thus reducing building time.

Alongside the persistent housing shortage, three additional challenges drive the transition towards modularization and industrialization in housebuilding in the Netherlands. The first challenge concerns the need to upgrade the existing housing stock in the Netherlands to substantially reduce energy consumption (Rijksoverheid, 2019a; Rijksoverheid, 2019b). Second, in line with national policies, the housebuilding sector in the Netherlands is about to enter a transition towards fully circular construction by 2050 (Rijksoverheid, 2019a; Rijksoverheid, 2019b). Third, the changing housing requirements also need to be considered given the trend towards smaller households. The latter is due to an aging population, the growth in the number of one-person households and also international migration in recent decades, which together have led to a greater diversity in residential preferences (Arnoldussen et al., 2017). Overall, these changes require the development and implementation of substantial innovations in the housebuilding sector. To a large extent, these challenges are not unique to the Netherlands but apply to many countries in the EU as well as to the UK (Eurostat, 2019a, b).

2.2. Modularity: a general introduction

Firms are looking for ways to improve the efficiency, sustainability and level of customization in housebuilding in a way that does not increase project risks, complexity and building costs. The sector has shown a growing interest in applying modern industrial construction methods based on product modularity (Barbosa et al., 2017; Bertram et al., 2019; Hofman et al., 2009). Following Salvador (2007), a product system is seen as modular to the extent that it has separable subsystems that can be combined in different ways to configure product variants. Modular

product systems are characterized by a one-to-one mapping between functions and physical subsystems and have standardized, decoupled interfaces (Ulrich, 1995). Decoupling implies that changes in one subsystem do not require changes in other interfacing subsystems (Baldwin and Clark, 2000) provided they remain within the boundaries of the interface specifications initially established (Hofman et al., 2016). This allows firms to select modular innovations and use them in combination with other unchanged subsystems to configure a new and improved overall system. Thus, within a modular product system, product subsystems (modules) are interchangeable, autonomous and individually upgradeable because the interfaces are standardized (Hofman et al., 2009; Ulrich, 1995). Product modularity also has the potential to substantially improve product and process sustainability by facilitating access to individual modules and components of the product system, thereby facilitating refurbishing, re-use and recycling (Chung et al., 2014; Kimura et al., 2001; Ma and Kremer, 2016; Okudan Kremer et al., 2013). This is especially relevant for modules that age more rapidly than parts they interface with, or that improve faster, for example due to higher innovation clock speeds, than other parts leading to an opportunity for modular upgrades of the system.

Fine et al. (2005) emphasized the need to balance modularity in product, process and supply chain designs when introducing a potentially successful modular product. These three dimensions of modularity encompass the following aspects:

Product modularity – modular products are characterized by a clear mapping between functions and components. As such, modules are relatively autonomous with loose coupling between modules that are connected with each other using standard interfaces.

Process modularity – modular products can be autonomously and independently developed and produced across time and space. That is, modules can be produced independently at different locations as long as they adhere to the predefined interface standards. Nevertheless, the selected production and manufacturing techniques set the economic territory (Dicken and Malmberg, 2001) which can be determined, in particular by various logistical and site operations restrictions (Blismas and Wakefield, 2009; Hwang et al., 2018; Lu et al., 2018; Rahman, 2013). Next, when brought together, modules can be installed

independently from each other and, over time, substitution and recombination is possible without the need to dismantle the whole system.

Supply chain modularity – Firms within a modular supply chain are loosely coupled to each other with a clear distribution of responsibilities at the module level reflecting a high level of interface standardization. To coordinate the development of modular design rules, including the product architecture and interface standards, firms initially depend on tighter integration and coordination among supply chain partners (Hofman, 2009). At a later stage, such design rules can function as industry standards and provide a template for new module developers - beyond those included in this initial supply chain network - that guides them in developing modules that will be compatible with the other modules in the overall system (Hofman et al., 2017).

In the following subsection we further operationalize Fine’s three-dimensional modularity concept when applied to the adoption of green modular innovations in the housebuilding sector.

2.3. Modularity in the housebuilding sector

Modularity in housebuilding has been the subject of study in various scientific articles (da Rocha et al., 2015; Doran and Giannakis, 2011; Halman et al., 2008; Hofer and Halman, 2005; Hofman et al., 2009; Lennartsson and Björnöt, 2010; Pero et al., 2015; Viana et al., 2017) and doctoral dissertations (Hofman, 2010; Jensen, 2014; Sheffer, 2011; Wolters, 2002). The modularity concept developed by Fine et al. (2005) with its three dimensions has demonstrated added value in describing and analysing product, process and supply chain modularity in the housebuilding sector (Voordijk et al., 2006; Wolters, 2002) and as a guide to introducing modular innovations in construction (Lennartsson and Björnöt, 2010). Based on the three-dimensional modularity concept, we have clustered the existing housebuilding literature on product, process and supply chain modularity in Table 1. Table 1 also provides an overview of the indicators that have been developed to characterize the level of product, process and supply chain modularity, ranging from low (integral) to high (modular).

Table 1
Modularity types and suggested indicators to characterize modularity level in the housebuilding sector.

Modularity concept	Typology	Indicators
Product modularity	Types of product modularity:	Product modularity indicators:
	<ol style="list-style-type: none"> 1) Variant 2) Core 3) Sectional 4) Bus (Sanchez and Mahoney, 1996; Wolters, 2002; Van den Thillart, 2002; Jensen, 2014)	<ul style="list-style-type: none"> • Distinctiveness of modules • Loose coupling between modules plus tight coupling within modules • Clear mapping between functions and components • Standardization of interfaces (da Rocha and Kemmer, 2018; Gosling et al., 2016; Hofman, 2010; Pero et al., 2015; Voordijk et al., 2006; Wolters, 2002)
Process modularity	Types of process modularity:	Process modularity indicators:
	<ol style="list-style-type: none"> 1) Volumetric pre-assembly 2) Pod pre-assembly 3) Panelized pre-assembly 4) Component manufacture & sub-assembly 5) Site-based manufacturing (Gibb, 1999; Hartley and Blagden, 2007; NAO, 2005; Ross et al., 2006; Taylor, 2010)	<ul style="list-style-type: none"> • Autonomous, independent production (in time and space) • Territorial economy (restricted ‘territory’ due to transportation limitations; location of co-makers/key component suppliers, etc.) • Substitution and recombination (coupling & interdependency) • Installation task interdependency (da Rocha and Kemmer, 2018; Gosling et al., 2016; Hofman, 2010; Pero et al., 2015; Voordijk et al., 2006; Wolters, 2002)
Supply chain modularity	Types of supply chain modularity:	Supply chain modularity indicators:
	<ol style="list-style-type: none"> 1) Closed system: all players directly engaged across project lifecycle, coordinated (by house builder) 2) Modular system: interlocked, fixed principal suppliers 3) Open system: loosely coupled and dispersed (autonomous) 	<ul style="list-style-type: none"> • Economic relationship: subcontracting vs partnering; distribution of responsibilities • Customer specification of decoupling point • Cultural proximity (embodied by social structure and working culture) • High-tech electronic proximity • Geographical proximity • Purchased object and availability (number of competitive suppliers) (da Rocha and Kemmer, 2018; Gosling et al., 2016; Hofman, 2010; Pero et al., 2015; Voordijk et al., 2006; Wolters, 2002):

2.4. The adoption of innovations, modular innovations and green modular innovations in housebuilding projects

Studies into the factors that affect the adoption of innovation in the housebuilding sector have received increasing attention in recent decades. In a recently conducted extensive literature review, 94 scientific articles were identified that addressed the adoption of various types of technology innovation in the housebuilding sector (Van Oorschot et al., 2020). The review also presents a conceptual innovation adoption framework that includes four categories of innovation adoption determinants and their underlying variables. The four categories (with a total of 21 underlying variables) are: (1) the influence of the environment; (2) the product’s characteristics and innovation attributes; (3) industry characteristics; and (4) adopter characteristics.

Studies addressing the adoption of modular innovations in the construction industry are still very few in number. Sheffer (2011) demonstrated, in her doctoral thesis, that, compared to integral innovations, modular innovations are much more likely to be adopted. This supports the claim that modularity could be viewed as a potentially valuable strategy to sustain innovation and change in the sector. Further, Azhar et al., (2013) identified “supply chain integration and effective collaboration among project stakeholders already in the early stages of the project” as a key factor in the adoption of modular construction. The importance of supply chain integration and the degree of coupling between the involved stakeholders have also been emphasized by Doran and Giannakis (2011) and Hofman (2010) who explored the application of modular practices in construction. To compete effectively with traditional on-site solutions, Doran and Giannakis (2011) observed an increase in supply chain integration for modular solutions. Hofman (2010) found that a higher degree of organizational coupling among innovation network members, together with the availability of product design rules, significantly improved the commercial success of modular innovations. Further, Azhar et al. (2013) identified several barriers that hinder the adoption and diffusion of modular construction: poor building design in terms of suitability for modularization; a lack of awareness of the benefits; non-availability of prefabrication units in the project vicinity; restricted site layout; and design rigidity. However, studies on the adoption of specifically green modular innovations in housebuilding projects are, to the best of our knowledge, unfortunately still lacking.

3. Research methodology

A multiple case study, involving three different cases, was conducted

Table 2
Overview of data sources per case.

	Sources of evidence	Details	Content analysis
Case 1: Modular renewable energy system	Interviews	Three interviews with the supplier (innovation manager: renewables), a contractor (technical director) and an installer (innovation manager) ^a .	Coding transcripts using ATLAS.ti. 6.2
	Documents	Technical product information.	Coding product information
	Focus group	One focus group with interviewees, another installer and experts in the field.	Coding transcript using ATLAS.ti. 6.2
Case 2: Modular Bathroom Pod	Interviews	Three interviews with the supplier (projects and concepts manager), contractor (innovation manager) and installer (project leader).	Coding transcripts using ATLAS.ti. 6.2
	Documents	Technical product information.	Coding product information
	Focus group	One focus group with interviewees and experts in the field.	Coding transcript using ATLAS.ti. 6.2
Case 3: Modular BIPV Roof	Interviews	Four interviews with the supplier (managing director), contractor (director), architect firm (architect) ^a and energy provider (business developer).	Coding transcripts using ATLAS.ti. 6.2
	Documents	Technical product information.	Coding product information
	Focus group	One focus group with interviewees, additional representatives from the organizations and experts in the field.	Coding transcript using ATLAS.ti. 6.2

^a These respondents did not attend a workshop.

to gain insight into factors that influence the adoption of green modular innovations in the housebuilding sector. This methodology was chosen because case studies allow one to retain holistic and meaningful characteristics of real-life events, situations and general settings. Moreover, case studies are particularly meaningful when studying a contemporary phenomenon within its real-life context (Yin, 2013).

3.1. Case selection

The selection of the case studies was governed by four criteria mirroring the key characteristics of green innovation and modularity:

- The modules in the case study should be key subsystems of a house (façade, roof etc.) with a one-to-one mapping to the elementary functionalities of a house. The modules will be typically self-contained, easily (de-)coupled, typically standardized with standard interfaces, and replaceable without affecting other components of the house (Baldwin and Clark, 2000; Hofman et al., 2016; Salvador, 2007; Ulrich, 1995).
- The modules should be innovative: new to the housebuilding market. In addition, the modules selected for the case study should be available on the market, have already been applied in one or several real projects, but still in the early stages of market entry (Lenderink et al., 2020; Rogers, 2003; Slaughter, 1998; Van de Ven, 1986).
- The modules included in the case study bring sustainability and efficiency improvements and thus be classifiable as green innovations. Moreover, the innovations should be clearly linked to sustainability policy (energy efficiency and circularity) in the housebuilding sector (Cillo et al., 2019; Tello and Yoon, 2008).
- The modules should require various resources from multiple stakeholders. This will be embodied in extensive knowledge spillover and multidisciplinary, inter-organizational cooperation working around various technological, organizational and geographical proximity barriers (e.g., Messeni Petruzzelli et al., 2011; Ardito et al., 2016, 2019b,a; Cillo et al., 2019).

These criteria ensured that the cases selected could be situated in the context of this study given their modular, innovative and green character. The three green modular innovations selected had all been recently developed by suppliers and implemented in housing projects in the Netherlands.

3.2. Data collection

Table 2 provides an overview of the sources that were used to obtain data for the case studies. For each case study, 3 or 4 interviews were conducted with key stakeholders from the companies supplying the green modular innovations, the contracting companies and the installation companies. In total, 10 interviews, varying in length from 50 to 90 min (average 60 min), were conducted with representatives from 10 different companies. The stakeholders who were interviewed held important managerial positions, possessed deep knowledge of their organization and were involved in the decision-making process surrounding adoption.

An interview protocol was created for the interviews (see Appendix A). A semi-structured approach was adopted to enable follow-up questions and include aspects that were considered relevant during each interview. All the interviews were recorded and transcribed. The transcripts were sent back to the respondents to verify the content and none had to be modified. The interviewees also provided documents that enabled us to refine the descriptions of the characteristics of the three green modular innovations under studied and of the adoption mechanisms. In answering our questions, the stakeholders explained the nature of the green modular innovations and their notable features, describing the process of adoption and explaining the key determinants of adoption. Validation workshops were held later (see Appendix B).

3.3. Data analysis

Data analysis involved examining, categorizing, tabulating, testing, or otherwise recombining, evidence to draw empirically based conclusions (Yin, 2013). The content analysis consisted of coding the interview reports using ATLAS.ti. 6.2. Coding consists of segmenting, separating and disassembling the data obtained during data collection into smaller units of information that are easier to handle, after which the data are reassembled and analysed (Mzembe et al. (2020) followed a similar procedure). The content analysis procedure recommended by Boeije (2010) was followed. First, every document was 'open coded'. This step consisted of a first order analysis of the interview reports. The data analysis primarily focused on the semi-structured interviews with key stakeholders because they would provide the best insights into the logic behind the decision of the project to adopt a green modular innovation. In the next step, 'axial coding' was employed to reorganize and reassemble the codes identified in the previous phase. The output of this step consists of themes and concepts and is considered an essential intermediary step towards theory building. These themes and concepts were then used as input for 'theoretical coding' where relationships between the themes and concepts – and the data fragments representing them – were identified. This step was guided by deductively drawing on theory as discussed in Section 2. Identifying the first-order open codes, the themes and concepts and, subsequently, the research propositions was supported by a data structure that consisted of various research notes and matrices as suggested by Miles and Huberman (1994). See Appendix C for more details about the data analysis.

3.4. Validating workshops

To validate the data collected in the individual interviews and the results of our data analysis, workshop sessions were organized and conducted for each of the three case studies. The workshops are best described as moderated focus group discussion sessions where the most important findings from the interviews and the data analysis were discussed with those involved in each case study (see Appendix B). The sessions focused on validating the major findings obtained from the individual interviews. These sessions allowed the participants to clarify their views and opinions and to discuss them with all the participants of the specific case study. Focus group discussions are inherently prone to bias such as group think. This was anticipated and guarded against in

two ways. The first was to establish a clear focus on validating previous findings whereby the attendees were explicitly asked to add context to the adoption variables identified from the individual interviews. Second, the group discussions were moderated by an experienced facilitator who was not involved in the interview and coding steps of the research. The three workshop sessions each had a duration of approximately 90 min. All the interviewees were invited to their respective workshop, and eight out of ten participated. In one of the workshop sessions, additional experts from the companies involved participated to add value to the discussion. The sessions were recorded for later transcription and to be able to code the major findings from each of the workshops. In every case, the focus group discussions provided support for the adoption variables found through coding the interviews in the previous step, and therefore we concluded that our research findings were robust for subsequent cross-case analysis.

3.5. Cross-case analysis

Once the data per case study was arranged in organized segments, a cross-case analysis took place following the recommendations of Miles and Huberman (1994) and Miles et al. (2014). The cross-case analysis adopted a variable-oriented approach where variables were compared across the three case studies. The case-specific determinants were compared with each other to arrive at generic conclusions with respect to the adoption variables. These adoption variables were derived following several iterations and re-examination of the case data and repeating the cross-case analysis (see Table 4). The eventual cross-case analysis was followed by an analysis of possible interrelationships between the identified adoption variables. Based on this analysis, it was possible to deduce four path models that determined the adoption of the green modular innovations in the three case studies. As a result, four propositions were formulated that could guide future research on the adoption of green modular innovations in housing projects.

4. Findings

4.1. Brief case descriptions

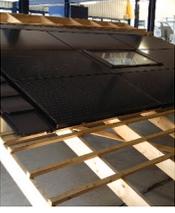
For our multiple case study, we selected three green modular innovations: a modular renewable energy system, a modular bathroom pod and a modular building-integrated photovoltaic (BIPV) roof. Table 3 presents an overview of the distinctive characteristics of the modules of this case study.

In terms of cleaner production in housebuilding, we calculated the potential carbon emission reduction for the green modular innovations applied in Cases 1 and 3. The carbon emission reduction results from the application of renewable energy technologies that lower the operational energy consumption of households. Although potentially applicable in many housing types, the most important market segment includes terraced, single family housing which we took as the baseline for our calculations. A typical single family household in the Netherlands consumes about 3260 kWh electricity for household appliances and 1080 m³ natural gas for heating and domestic hot water, equating to an annual carbon emission of some 3880 kg CO₂. The calculations suggest that installing the modular renewable energy system (Case 1) and the modular building integrated photovoltaics (Case 3) will reduce carbon emission by 11 % and 44 % respectively. Given that often energy efficiency technologies are installed in combination, we also calculated that a combined installation would result in a reduced carbon emission of about 56 % (see Fig. 1). Due to a lack of data on the material consumption and waste production in Case 2 relative to traditional construction practices, we were not able to calculate the expected positive environmental impact of a reduction in materials used (embodied energy and embodied carbon).

Energy efficiency policies were the main driver in developing the renewable energy system (RES) in Case 1. Growing concerns about

Table 3

Description of the modules studied: all are considered key parts of the overall housing system in which they are applied.

Case study	Module	Integrated functions	Performance target	Physical components	Process	Supply chain
Modular renewable energy system ^a - ‘Engine’ that provides a low energy consumption indoor climate solution.		Heating, cooling, domestic hot water (DHW), indoor climate control and comfort.	Improved indoor comfort, low energy costs, ventilation and healthy indoor climate, rapid installation.	Heat pump unit, water tank, heat recovery unit, ventilation recovery unit and a system monitoring unit.	Module pre-assembled at central production location, transported to construction site and installed by certified installers. The key components are developed and produced in-house, complemented by various components from second-tier suppliers.	The overall building-level performance depends not only on the module but also on the integrated performance of various other housing subsystems. A clear distribution of responsibilities between unchanging principal suppliers ensures overall performance.
Modular Bathroom Pod ^b - Pod housing an off-site built bathroom.		The module provides all the functions provided by a conventional bathroom.	High quality, durability and customizability, plug-and-play installation, traditional appearance and ten-year guarantee.	Compound walls made of bio-based materials (flax, wood and plaster), vinyl wall covering complemented with traditional bathroom components (toilet, washbasin, shower etc.)	Prefabricated modules are transported to the construction site and installed. The bio-based bare structure of the pod is developed and produced in-house, complemented by various components from second-tier suppliers.	The module forms part of a housebuilding system based on a so-called one-piece-flow approach and a modular construction process. A modular supply chain was instigated involving various module suppliers.
Modular BIPV Roof ^c - Roofing solution to provide shelter and generate electrical power.		Watertight, generation of electrical power, roof insulation, and allow daylight entry to illuminate roof space.	Simple to install, increased comfort, visually attractive and financially attractive.	Integrated solar panels, insulation layer and skylight.	The three core components are off-the-shelf products produced by three established suppliers. The system is installed by a specialized installer under the supervision of the photovoltaic system supplier in its role as system integrator.	The BIPV roof is offered as a one-stop-shop modular product by a supplier of PV systems. The supply chain can be characterized as an open and dispersed system with loose couplings between the key suppliers involved.

^a) Retrieved from: <http://zakelijk.ithodaalderop.nl/producten/systemen-en-concepten/flat-energy-cube>.

^b) Picture by the author.

^c) Picture by the author.

achieving a healthy and comfortable indoor climate also played a role. In addition to a highly insulated building envelope, various renewable energy technologies are required to construct what is seen as an energy efficient dwelling including solar photovoltaic systems, heat pumps and ventilation units with heat recovery to provide heating, ventilation and hot water. Conventionally, these technologies would be installed separately from each other in a dwelling. This is rather inefficient and it is not straightforward to make all the subsystems work as a single “system”. Further, the technical installation takes up a lot of space and installation on site is labour intensive. The RES was developed to address these inefficiencies. The RES is designed to provide heat, ventilation and domestic hot water for housing in a temperate maritime climate, and therefore appropriate for the Dutch housing market. The RES can be installed in both newly built and major renovation projects. Its application in housing projects requires close collaboration between the supplier, the installer and the main contractor. The key stakeholders in this case study, a contractor and an indoor-climate systems supplier, met through a national network forum. The members of this network share the same mission to stimulate the transition towards an energy efficient housebuilding sector. Inspired by this mission and in contrast to traditional housebuilding, these actors are motivated to share resources and work closely together to solve various problems related to technological interfaces. As such they developed a shared technological and organizational knowledge base as required to conduct housing projects involving innovative green modules. The RES is currently diffusing into the Dutch housing market in both new-build and energy-efficient renovation projects.

The main drivers for Case 2 were recurring building quality issues

and low production efficiency. A group of supply chain partners developed a long-term collaboration within a so-called ‘Inno Concept Building’ chain. Together they developed a business proposition to change traditional housebuilding practices by transcending one-off project collaborations and by implementing an industrialized one-piece-flow production line. As with Case 1, this network forum appeared to be critical in addressing the various proximity barriers which are a characteristic of the highly fragmented housebuilding sector. This resulted in the development and application of a fully prefabricated bathroom pod which can be installed without any additional work on site. Besides quality and efficiency advantages, the bathroom pod resulted in a more environmentally friendly solution due to a substantial reduction in waste during prefabrication and the application of bio-based materials in the basic pod structure. To date, these bathroom pods have not been produced and installed in large quantities, and both the product and the supply chain seem to be treading water.

The developments in Case 3 were motivated by energy efficiency policies introduced for the housebuilding sector. These stimulated the development of renewable energy systems in general. The modular, building integrated photovoltaics (BIPV) roof system, a relatively simple energy roof system, facilitates various functionalities. These functions relate to providing insulation, daylight and energy that can be linked to specific components: roof boarding, a dormer window and photovoltaic panels. In addition to energy efficiency policies, the poorly valued aesthetics of PV panels installed on tiled roofs also stimulated the development of the BIPV roof system. The BIPV roof system integrates the photovoltaic panels in the roof design, giving the appearance of a traditional tiled roof. The BIPV roof system is composed of three core

Table 4
Variables affecting the adoption of modular innovations.

Variable	Case 1: Mod. renewable energy system	Case 2: Modular Bathroom Pod	Case 3: Modular BIPV Roof
1a. Relative advantages (construction duration; replicability; integrating functions)	– <u>Replicability</u> : flexibility of components allows adaptation to the demands of different dwellings. <u>Integrating functions</u> in a single module satisfies different end-user requirements and diminishes the number of suppliers a contractor has to work with.	Satisfies desire to reduce <u>construction duration</u> of a dwelling. <u>Replicability</u> : flexibility of components allows it to be adapted to the demands of different dwellings. <u>Integrating functions</u> reduces the number of suppliers a contractor works with and improves overall quality by reducing the number of deficiencies as a result of task dependency issues.	<u>Reducing installation duration and disturbance</u> caused to householders. <u>Replicability</u> : flexibility of components allows adaptation to the demands of different dwellings. The <u>integration</u> of three functions provides a module that fully satisfies the needs of potential customers. At the same time, it offers an attractive and appealing <u>visual appearance</u> .
1 b. Factors diminishing (perceived) relative advantages (trialability; latent need; time-lag)	End-users cannot <u>perceive or experience</u> the comfort provided by the module before adopting it. Some of the benefits claimed by the supplier encompass <u>latent client needs</u> and link to remote issues such as climate change rather than provide immediate benefits. Adoption hindered by <u>time-lag</u> issues related to the period before a client benefits from the module.	–	End-users cannot <u>perceive or experience</u> the comfort provided by the module before adopting it. Some of the benefits reported by the supplier encompass <u>latent client needs</u> and link to remote issues such as climate change rather than providing immediate benefits. Adoption hindered by <u>time-lag</u> issues related to the period before a client benefits from the innovation.
2. Investment costs and low-cost procurement practices	The distribution of lifecycle costs discourages end-users from module adoption (<u>high initial costs</u> balanced by low lifecycle costs and reduced energy bills). <u>Procurement</u> : selecting a supplier should be based on the price–quality relationship but is often based on the lowest price.	The <u>initial costs</u> of a prefabricated bathroom should not be more than a traditional bathroom. <u>Procurement</u> : selecting supplier based on a positive price–quality ratio would encourage module adoption.	The <u>initial costs</u> of the full roof system are compared to the cost of just PV panels and, therefore, the module is perceived as too expensive. <u>Procurement</u> : adoption by end-users is hindered if they acquire products (or modules) based on the lowest price.
3. Supply chain integration	Long-term partnerships are not only a primary condition to develop green modular innovations but also to sustain their adoption. The modular nature of the product requires the reallocation of responsibilities and liabilities and also long-term commitment to ensure the supply of specific components and to benefit from economies of scale. This would ensure a competitive product based on quality and price.	Long-term partnerships are not only a primary condition to develop green modular innovations but also to sustain their adoption. The modular design of the bathroom requires the reallocation of responsibilities and liabilities and also long-term commitment to ensure the supply of specific components and to benefit from economies of scale. This would ensure a competitive product based on quality and price.	Long-term partnerships are not only a primary condition to develop green modular innovations but also to sustain their adoption. The modular design of the roof requires a reallocation of responsibilities and liabilities and also long-term commitment to ensure the supply of specific components and to benefit from economies of scale. This would ensure a competitive product based on quality and price.
4. Design rules and standards	Many kinds of interfaces are technically possible, however agreeing on them is a <u>time-consuming</u> process. Implementation in demonstration projects makes it easier to confirm the effectiveness of interfaces – connections can be replicated across projects.	Agreements about standards and standard interfaces are difficult and <u>time-consuming</u> to establish. Standardization and standard product interfaces (despite the high development costs) sustain the application of the module across projects. To adopt the module, contractors also have to implement new working/installation processes, resulting in a subdivision of tasks and responsibilities.	– Having standards and design rules available (initially developed as a key component of a deep renovation system) facilitates the module installation process.
5. Division of responsibilities across the supply chain	–	–	To adopt the module, contractors only need to make agreements with a single module supplier whereas, traditionally, they would have to negotiate separate agreements with the suppliers of various components.
6. Availability of adequate skills and knowledge	A shortage of professional firms to properly install the module hinders its adoption.	Implementation of the module requires a multidisciplinary crew and multi-skilled labour.	Using a multi-skilled crew, dedicated exclusively to installing the module, helps to generate knowledge and progressively improve the installation process.
7. Innovation maturity: guarantees and liabilities	Guarantees on the module across its operational lifetime would enhance adoption by potential end-users.	Guarantees on the module across its operational lifecycle would enhance adoption by potential end-users.	–
8. Market maturity	Limited awareness and immaturity of the market: housebuilders are unused to conducting projects based on performance specifications rather than product specifications.	Performance specifications reduce uncertainties related to the installation process of the module.	–
9. Supplier characteristics: corporate branding	–	The contractor is more likely to choose a supplier with a good reputation and with stable production volumes and known quality.	Having a large and stable company with a good reputation supporting the modular BIPV roof increases the likelihood of adoption.
10. Energy Efficiency and Building regulations	Stricter energy efficiency regulations support the adoption of sustainable technologies, including green modular innovations.	–	Stricter energy efficiency regulations support the adoption of sustainable technologies, including green modular innovations. The minimum energy performance required by law (the Building Code) is understood by contractors as the highest energy performance they will provide to customers.

components which are independently available on the market. As such, the energy roof is considered modular on both the building and the product levels because standardized interfaces based on loose couplings have been developed to connect the modular BIPV roof to the building and to link the three distinctive core technologies. The modular BIPV roof is supplied to the market using a one-stop-shop concept, i.e. a single supplier is responsible for the design, engineering, installation and maintenance of the full roof system. As a result, some tasks normally conducted by the contractor are shifted to the BIPV supplier. In contrast to Cases 1 and 2, the application of the BIPV roof in Case 3 was not facilitated by a network forum but through the close proximity of the firms involved. The BIPV roof system can be used in new construction projects as well as in energy-efficiency renovation projects. Currently, the BIPV roof system integrator is attempting to get the product adopted on a large scale to move beyond its current status of small-scale application in demonstration projects.

4.2. Identification of four path models for the adoption of green modular innovations

As explained in Subsection 3.4, we identified, during the process of coding the interview transcripts and carrying out a cross-case comparison, 10 variables that affect the adoption of green modular innovations in housing projects (Table 4). At the same time, we also found interrelationships between several of the adoption variables. By evaluating the 10 adoption variables and their possible interrelationships in each of the three case studies, we were able to deduce four path models that determine the potential adoption of green modular innovations in housebuilding projects (Figs 3 – 5). This subsection describes these four paths and formulates associated propositions.

4.2.1. Supply chain integration and green modular innovation adoption

Compatibility is a key variable in explaining innovation adoption (Rogers, 2003). In a modular product architecture, the compatibility of modules is primarily managed through a clear set of design rules that specify standardized interfaces between modules (for a complete list of design rules see Baldwin and Clark, 2000 and Hofman et al., 2016). Provided suppliers develop modules that conform to such interface standards, the result is a collection of modules that can be configured into many different end-systems that offer a consistent, well integrated combination and a related high overall performance. Hofman et al. (2009) further observe that: “The success of design rules depends on the extent to which they are accepted by upstream and downstream firms and final customers.” However, they go on to caution that developing such design rules requires intensive upfront coordination and investments that typically cannot be recovered through a single project but only at the cross-project level through multiple applications. Such longer-term collaborations lead to what can be referred to as supply chain platforms (Hofman, 2010; Hofman et al., 2009, 2016). Product design rules provide compatibility standards within a supply chain network but not necessarily across supply chain networks. If, at a later stage, these product design rules diffuse at the industry level, this can facilitate the emergence of an construction business ecosystem with complementary firms supplying modules that can be innovated at various paces while remaining highly compatible because they adhere to the predefined set of interface standards. The governance of such a platform ecosystem and the creation and capture of value in such platform ecosystems requires very different practices than conventional linear supply chains (for a fuller discussion see Tiwana (2013) and Cabigiosu et al. (2013)).

However, to facilitate the initial development of the requisite design rules requires early-stage integration at the supply network level. In all the three cases we observed, the development of modular design rules initially required significant managerial effort, creating, as expected, a need for tighter supply chain integration. Participants highlighted that, to develop design rules and standards, stable relationships built on regular communication and based on trust and transparency were

needed. Developing a shared vision appears to be key in building a strong coalition around a green modular architecture (Gawer and Cusumano, 2014; Hofman, 2010; Taylor, 2005).

Design rules reduce the managerial effort required to implement green modular innovations in subsequent projects, and thus have a positive effect on adoption. However, establishing an initial agreement over design rules and standards is time consuming and subsequently hinders the adoption of the green modular innovation in its early stage of diffusion. In terms of Fine et al.’s (2005) modularity concept, the development of supply chain modularity, in particular in terms of economic organization (network), mode of governance (partnering), cultural proximity (community based) and customer order specification (modify to order), is a precondition for full product and process modularity. This led to the development of the following propositions (see also Fig. 2):

Proposition 1a. *Supply chain integration by means of stable long-term collaboration has a positive effect on the willingness to develop modular design rules.*

Proposition 1b. *Modular design rules function as compatibility standards across modules; their diffusion and use among partners increases the adoption of green modular innovations.*

4.2.2. The relative advantages of green modular innovation adoption

The interviewees in all three case studies explained the advantage of their modular innovations relative to conventional practices in terms of their energy and material efficiency gains in both the housebuilding process as well as in later use of the building. Furthermore, the ability to re-use the module designs at the cross-project level provided increasing returns due to learning effects further raising module quality and their perceived relative advantage. However, the positive effect of the relative advantage of the product modules was mitigated by other consequences of their integrative nature, and the degree of function integration, of the product modules. In a traditional housebuilding process, with a fragmented supply chain, the contractor adds and captures value at the project level by integrating a large diversity of components and services that are supplied by different parties. However, by integrating components and their related functionalities in a green modular innovation, value creation and capture is shifted upstream in the value chain from the contractor to the module suppliers making the previous integrative efforts by contractors obsolete. For example, in the case of the modular BIPV roof, the contractor only needs to make an agreement with a single module supplier of the complete roofing solution whereas, traditionally, they would have to negotiate separate agreements with suppliers of PV panels, insulation material and skylights. In this example, component and function integration in a single module required a restructuring of the supply chain. Interviewees reported that contractors often showed resistance to this displacement of design and production responsibilities and the related value capture.

Therefore, we conclude that the alignment between modules that integrate functions and contractor-supplier relationships is in part driven by the willingness of the contracting company to accept a different supply chain format that is tuned to the new modular product architecture. This conclusion is in line with earlier findings by Hofman et al. (2009) who outlined four contingent drivers of the alignment between product modules and contractor-supplier relationships: the degree of variety in customer demand; the extent of the required supplier investment; the extent of the dependence on supplier knowledge; and the intentions of both the supplier and the buyer in a relationship. In our study, we particularly found support for the last of these drivers. Thus, in line with Fine’s (2005) modularity concept, if the involved stakeholders are not able to align supply chain modularity with product and process modularity, it is unlikely that the green modular innovation will be adopted in housebuilding projects.

The reluctance of housebuilders to hand over some of their responsibilities to module suppliers seems to go against the development

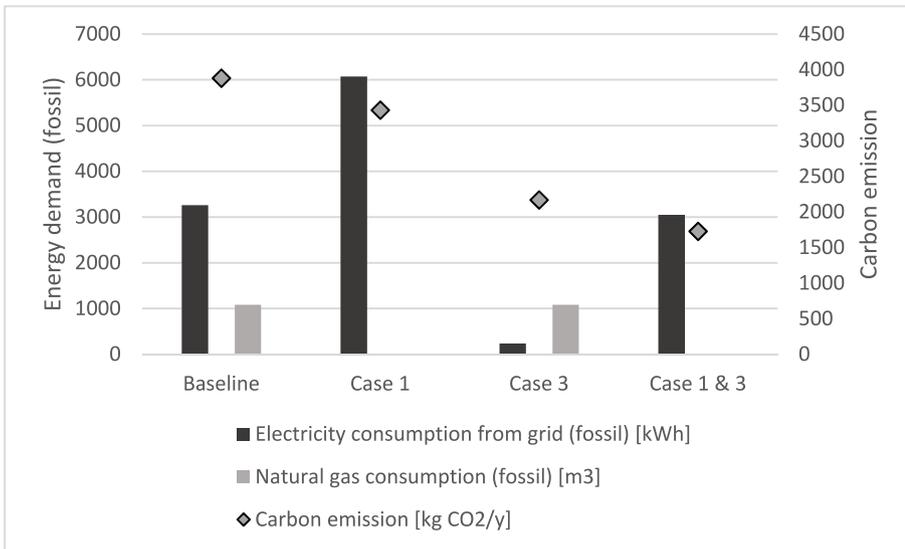


Fig. 1. Impact of the adoption of a modular renewable energy and modular BIPV roof in terms of cleaner production in housebuilding.

Baseline: The renewable energy technologies are considered only for moderately well insulated housing units equipped with a gas boiler for heating and domestic hot water. This includes single family terraced housing constructed after 1992 (introduction of new Building Code) and housing units which have been renovated to improve their energy efficiency. Based on housing market statistics we estimate that, in the most optimistic scenario, the market potential of the modular renewable energy system and the BIPV roof is about 1.7-2 million housing units.

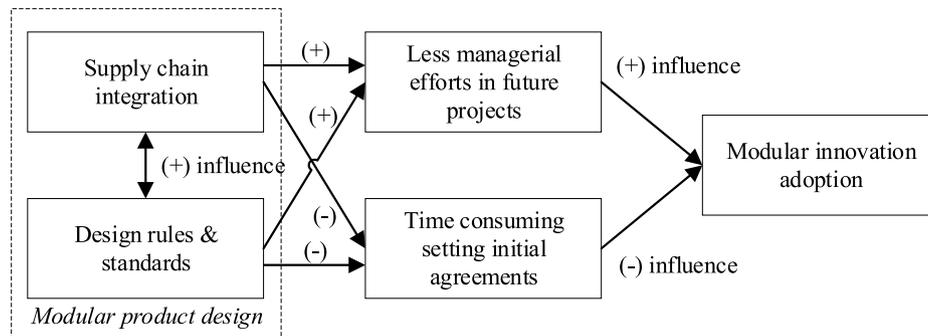


Fig. 2. The first path explaining how supply chain integration leads to green modular innovation adoption.

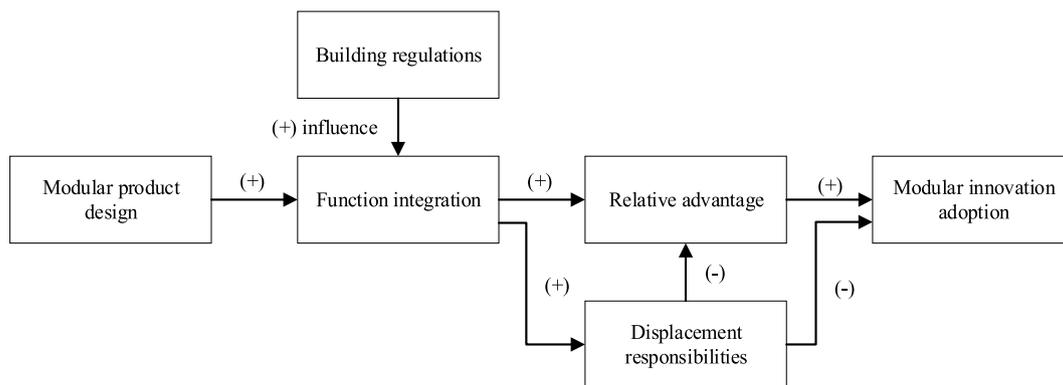


Fig. 3. The second path explaining how the relative advantages of a green modular product design lead to adoption.

of green modular innovations. On the one hand, housebuilders do recognize the advantages of green modular innovations in complying with stricter energy efficiency regulations but, on the other hand, they are hesitant about handing over responsibilities to module suppliers. This has to do with the fact that they see the transfer of responsibilities as a threat to their current business model, because value creation and capture shifts upstream to suppliers resulting in less added value to the housebuilder. At the same time housebuilders remain fully liable for the functioning of all the integrated modules. This reduces the willingness to accept the risks related to adopting novel green modular innovations.

Further, to benefit from their relative advantages, the modules need

to be applied in housebuilding projects and this will require specialized skills and knowledge. This includes specialized design skills to integrate modules into an overall building design and operate within set parameters. Once a design has been finalized, specialized labour skills are required to install, commission, maintain the green modular innovations, and eventually to remove them for recycling (Blismas and Wakefield, 2009). Some of the interviewees from the module suppliers indicated that these skills and knowledge, pertaining to both design firms and installers, have yet to be developed. It is therefore concluded that traditional solutions may well be implemented rather than modular product systems due to the fact that specialized design and

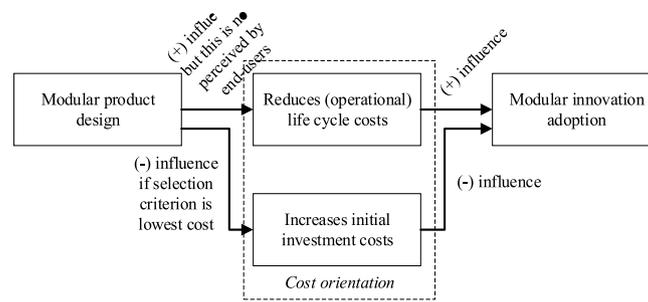


Fig. 4. The third path explaining how a low-cost orientation influences the acquisition and adoption of modular products.

commissioning skills and knowledge are not readily available. Combining these insights led to the development of the second path and associated propositions (see Fig. 3):

Proposition 2a. *The perceived relative advantages of green modular innovations have a positive effect on adoption.*

Proposition 2b. *The inability to displace responsibilities and control of operations along the supply chain has a negative effect on the adoption of green modular innovations.*

Proposition 2c. *Stricter building regulations regarding energy and material efficiency have a positive effect on green modular innovation adoption.*

Proposition 2d. *A lack of modular design knowledge at the project level has a negative effect on green modular innovation adoption.*

Proposition 2e. *Lack of specialized mounting, maintenance and eventual removal skills have a negative effect on green modular innovation adoption.*

4.2.3. *Lowest-acquisition-cost orientation and its effect on green modular innovation adoption*

Total cost of ownership (TCO) includes the cost in acquiring an asset plus the costs of its operation throughout the product’s lifecycle. Blismas et al. (2005) argue that the decisions made regarding adopting energy efficiency products are too often based on acquisition costs rather than total value (and total costs) offered. This is problematic for the adoption of modular products as such products tend to combine a higher purchasing price with reduced operating cost due to increased energy efficiency. Focusing on the supply side of the value chain, our multiple case study indeed shows that the reluctance of contractors to adopt green modular innovations in part emanates from their lowest-cost-price considerations when considering acquiring and processing products. Further, house buyers also perceive the green modular innovations as

expensive because they ignore the savings in operational costs when considering acquisition. Furthermore, buyers who do adopt a longer horizon when evaluating the total costs of ownership tend to undervalue the projected energy efficiency improvements and related operational cost savings because of the high perceived uncertainty they attach to these novel solutions. The lowest-cost-price orientation of contractors is thus strengthened by the house buyers reluctance to install these green modular innovations because they give energy efficiency a low priority, and fear cost increases and other problems due to the novelty of these technologies (see, for example, Hoppe (2012) and Sunikka (2006, 2017)). Moreover, adequately evaluating product modules appears to be too complex for many potential adopters. For example, with the modular BIPV roof, potential clients do not always perceive that they would be acquiring not only PV panels, but also improved roof insulation, a sustainable energy system, natural daylight and ventilation, all leading to a more comfortable and healthier internal environment. To boost adoption of such energy efficiency products, lifecycle costs need to be more strongly emphasized to increase understanding of value rather than just direct material and labour costs (Blismas and Wakefield, 2009). Although this cost-based mechanism does not fit directly within Fine’s modularity concept, it can be considered a key contingency variable reflecting the innovativeness of modular products (Pero et al., 2015; Sheffer, 2011), i.e. the novelty of modular products perceived by the involved stakeholders (Caridi et al., 2012; Garcia and Calantone, 2002). The third path links to the following propositions (see Fig. 4):

Proposition 3a. *The shift in the product cost structure across the lifecycle of a green modular innovation has a negative effect on green modular innovation adoption.*

Proposition 3b. *Low-cost procurement strategies (e.g., fixed price contracts awarded on lowest tender) have a negative effect on green modular*

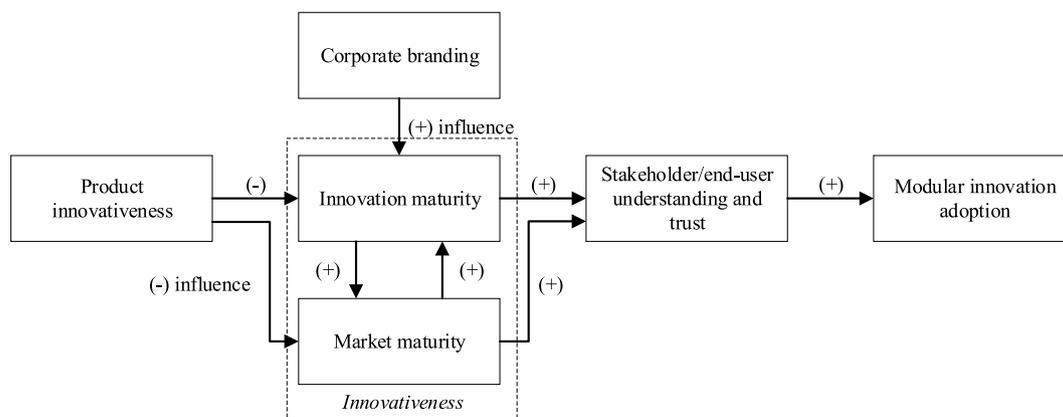


Fig. 5. Fourth proposed mechanism influencing green modular innovation adoption.

innovation adoption.

4.2.4. Green modular product innovativeness and adoption

Trialability and observability are seen as vital for the adoption of innovations (Rogers, 2003). This is problematic when the innovation, as with the green modular innovations in our case study, is in an early stage of market adoption. The case study indicated that intangible benefits, such as lower energy bills and an improved indoor climate, are only fully taken on board if they can be experienced, and therefore it is challenging for housebuilders to convey the benefits that potential end-users will experience. The very limited number of green modular innovations installed does not allow early adopters to rely on experience of previously installed products. The first problem is that the benefits of green innovations, such as the modular renewable energy system and the BIPV roof, cannot be perceived until the products are installed in the dwelling. As such, the cost benefits from applying the green modular innovations of Case 1 and 3 cannot be perceived until the dwelling is inhabited and in use. Second, increased comfort or a healthier indoor climate are features of the product that cannot be easily experienced by potential adopters as they are not easily observable. As the added value of the green modular innovations considered in this study are intangible performance improvements or a new experience, and they are at an early stage of adoption, suppliers and contractors need to find alternative and innovative ways to let end-users experience the advantages of these products. The respondents considered this to be an essential part of maturing the green modular innovations.

In addition to the difficulty in understanding the performance of green modular innovations due to their current novelty, the suppliers of the green modular innovations included in our research indicate that adoption is further complicated by uncertainties perceived by both housebuilders and clients about the performance of their green modular innovations. One way to overcome this could be to provide performance guarantees and accept liabilities in order to gain trust that a green modular innovation is sufficiently mature. However, carrying out projects based on 'performance specifications', rather than the product specifications normally applied in housebuilding, would be unconventional and this further hinders green modular innovation adoption. Some of the green modular innovation suppliers referred to this as a "market maturity barrier" and commented that stakeholders within the housebuilding supply chain are inexperienced and cautious when it comes to working with such novel practices. Product branding was mentioned as a possibility to lower this barrier because a strong corporate brand contributes to a housebuilder's perception that there are less risks and uncertainties in adopting a supplier's product.

To summarize, this mechanism underlines the negative effect of product innovativeness on adoption and the importance of creating mechanisms to overcome this inertia and encourage adoption. These mechanisms relate to both the contingent variable of innovativeness in the housebuilding sector and to Fine's modularity concept: not only the network structure but also the division of liabilities and guarantees across the supply chain are affected. The fourth path combines the following propositions (see Fig. 5):

Proposition 4a. *Innovativeness has a negative effect on the adoption of green modular innovations.*

Proposition 4b. *Low levels of innovation maturity have a negative effect on the adoption of green modular innovations.*

Proposition 4c. *Low levels of market maturity have a negative effect on the adoption of green modular innovations.*

Proposition 4d. *Corporate branding, expressing the reputation of a supplier, has a positive effect on the adoption of green modular innovations.*

5. Discussion and conclusions

5.1. Contribution

This multiple case study is among the first to study the mechanisms that affect the adoption of green modular innovations in the housing sector. Large scale adoption is regarded as essential since green modular innovations could significantly contribute to the decarbonization of both new and existing housing stock. The study addresses an important gap in the literature identified by Cillo et al. (2019) concerning the lack of empirical evidence on factors that enable or hinder sustainable practices. Our multiple case study was guided by two research questions: 1) What determining factors and mechanisms influence the adoption of green modular innovations in the housebuilding sector? and 2) To what extent can the theory on modularity help to explain the adoption, or failure, of green modular innovations in the housebuilding sector?

In addressing these research questions, this paper contributes in two ways. First, the present study integrates two independent streams of research on innovation adoption and modularity to assess the adoption of green modular innovations. Based on an in-depth assessment of adoption variables, we identified four paths that potentially lead to the adoption of green modular innovations. These paths indicate how and why modular housing products are adopted. Second, our study provides empirical evidence on the effect of modularity on adoption in line with the three dimensions of the modularity concept proposed by Fine et al. (2005) by tying the four adoption mechanisms together in a coherent framework. These contributions will be discussed in more detail in the remainder of this section.

The three case studies revealed 10 variables that influence the adoption of green modular innovations. By evaluating, for each of the three case studies, these adoption variables and their possible interrelationships, we were able to deduce four path models that determine the potential adoption of green modular innovations. For each path we have formulated associated propositions.

The first path underlines the importance of supply chain integration in that this can overcome the innovation inertia embodied in traditional construction practices. That is, supply chain integration is a precondition for increasing cross-company collaborative practices. It can create the space to allow standard interfaces and design rules to be created, aspects which are traditionally considered to be time consuming, complex to achieve and lacking added value. The identification of this path is supported by previous construction management research into barriers to innovation in construction and housebuilding (Lindgren, 2018; Sheffer, 2011; Taylor, 2005).

The second path reflects how the integration of functions in a green modular innovation can give it an advantage over traditional building approaches (enhanced product quality, improved sustainability and reduced construction time and costs). However, we also saw that the integration of functions within a green modular innovation can have implications for the division of tasks and responsibilities among the supply chain partners. This influences the willingness of a contracting company to make agreements with, possibly new, partners in the supply chain and their willingness to delegate responsibilities to suppliers. The second path we identified reflects this, that a modular product design also has implications for the supply chain organization: beyond developing a green modular innovation with appropriate standard interfaces and design rules, there also needs to be a clear allocation of liabilities and responsibilities across the supply chain partners (Cabigiosu and Camuffo, 2012; Colfer and Baldwin, 2016). This identified second path in particular gives support to Fine's modularity framework (Ellram et al., 2007; Fine et al., 2005).

The third path shows that innovation adoption is heavily influenced by lowest cost considerations. Although economies of scale and scope could potentially reduce the initially high cost of acquiring a modular product system, the added value provided by the integration of functions in a module leads to an increase in the purchase costs of the product

relative to its traditional solutions. Adopters do not associate this increment in the initial cost with the delivery of additional benefits and potentially lower total costs of ownership (Goodier and Gibb, 2007; Pan et al., 2008). For example, the cost-saving benefits of modular innovations that reduce operating costs and improve energy performance and the indoor climate are poorly perceived by end-users, discouraging their installation by contractors. In addition, traditional procurement practices do not encourage the adoption of best-value-for-money solutions, but rather look for the lowest purchase costs. Although this path cannot be associated with modularity theory, it can be considered as a contingency mechanism linked to innovation barriers in the housebuilding sector (Pero et al., 2015; Sheffer, 2011).

The fourth path explains how the current immaturity of the three green modular innovations, whose added value is then difficult for their potential beneficiaries to perceive, prevents end-users from adopting them; thereby discouraging modular innovation adoption in the industry. The role of innovation maturity has been discussed in the innovation adoption literature (Gan et al., 2015; Zhang et al., 2014). Here, our research has particularly revealed that increased innovation maturity, expressed by the availability of guarantees and liabilities, would have a positive effect on the adoption of innovative green modular innovations. Further, our research has also shown that market maturity tends to encourage the adoption of green modular innovations. This effect of market maturity refers to the notion that stakeholders within the housebuilding supply chain are inexperienced and cautious when it comes to innovative modular innovations. This was also concluded in a study conducted by Wolters (2002).

As a second contribution, we have provided empirical evidence that supports Fine's modularity framework (Ellram et al., 2007; Fine et al., 2005) and the claimed effect of modularity on innovation adoption. To our knowledge, this is one of the first in-depth empirical studies to explicitly link innovation adoption to modularity theory. Studied through a modularity lens, i.e. applying Fine's three-dimensional modularity concept, we derived four paths associated with the adoption of green modular innovations. These paths and their associated propositions fit with and refine Fine's modularity concept in the context of the housebuilding sector: coherence of the product, process and supply chain modularities shape the boundary conditions under which green modular innovations will potentially be adopted.

What does this all mean for the adoption of green modular innovations? From the case studies, we have learnt that it is not easy to implement green modular innovations that require far-reaching technological and organizational coordination in a housebuilding project. The involved supply chain partners have to develop a shared technological knowledge base and develop an organizational and cultural context which facilitates efficient knowledge sharing and a dyadic and collective learning culture. That is, partners have to achieve a close technical and organizational proximity to each other. Stable coalitions typically operate within a region, and the relatively close geographical distance between partners further facilitates knowledge spillover and close collaboration. This finding corresponds with the literature on geographical, technical and organizational proximity barriers that complicate inter-organizational collaboration and innovation (Knoben and Oerlemans, 2006). Thus, green modular innovations, at least in their early stages of market introduction, are most likely to be adopted and applied across housing projects when constructed by a stable coalition of supply chain partners. This conclusion also indicates what is required to cross boundaries and get green modular innovations adopted in other housing systems and projects. However, from the experiences of the respondents in the conducted case studies, and supported by the literature, we would not expect innovation spillovers to happen easily because the typically loosely coupled network structure of the housebuilding sector is not conducive to knowledge sharing and learning. Knowledge spillover and learning will not take place unless the explorative way of learning in projects is complemented by an infrastructure of feedback loops that facilitate the exploitation of the lessons

learnt at the organizational level, where feed forward to follow-up projects, with other network partners, can be instigated (Bygballe et al., 2015; Bygballe and Ingemansson, 2014; Gadde and Dubois, 2010; Gann and Salter, 2000).

5.2. Management and policy implications

An implication of this study for innovation managers in the housebuilding sector is that the application of the developed framework and propositions can support an increase in the adoption potential of their green modular innovations in the early stages of market entry and market formation.

The case studies further show that energy efficiency regulations set by the Dutch government are a key driver of the development of green modular innovations. In addition to energy efficiency regulations, a policy mix directed at providing capital, facilitating technology transfer and supporting universities and public research institutes (Feldman and Kelley, 2006; Klette et al., 2000; Martin and Scott, 2000) could contribute to setting standards and increasing investment in green modular innovations (Bertram et al., 2019; Tambach et al., 2010; Van Doren et al., 2020; Wuni and Shen, 2020). From a policy perspective, we can derive three implications from the results of this study.

First, our research indicates that the government should adopt a more directive role by prescribing, where appropriate, green modular innovations. For example, coercive pressure from the government has been found essential for the adoption of the 'Building Information Model' (BIM) across various countries. In the Netherlands, the use of BIM has been mandated by the Directorate General for Public Works and Water Management and the Government Buildings Agency in specific projects (Cheng and Lu, 2015; Papadonikolaki, 2018). However, since the Dutch government is not a major client in the Dutch housing sector, modularity needs to be mandated in a different way. This could, for example, be through covenants with clients and builders in the housebuilding sector or by placing preconditions on land provided for new houses.

Second, the government could assume a facilitating role to stimulate green modular innovations. For example, the government could stimulate and support the development and implementation of quality certification standards and warranties to inform clients and give them confidence about the quality and added value of adopting green modular innovations. Compared to other markets, such as consumer durables, warranties for construction products are not as well developed or applied (Rose and Manley, 2012). A rare example of where they have been applied is the application of performance specifications and warranties in US highway and bridge construction (Guo et al., 2005).

Third, the government could also play a supporting role by introducing financial measures to stimulate modular housebuilding and green modular innovations. This includes measures such as providing specific low-interest loans, applying a low VAT rate and long-term subsidies to stimulate specific green modular innovations.

5.3. Conclusions and recommendations for future research

This study is not without its limitations and from this various directions for future research can be derived. First of all, to explore the robustness of the findings the multiple case study could benefit from additional "polar type" cases (Eisenhardt, 1989; Eisenhardt and Graebner, 2007). Therefore we suggest to enrich this study with cases selected along the dimensions success versus failure innovations and modular versus systemic innovations. Second, although we involved highly knowledgeable respondents in our study who reflected on the adoption of green modular innovations from diverse perspectives, we did not find evidence for all the adoption variables found in literature, see Appendix C for an overview of these variables. Although these adoption variables were not mentioned by the respondents, it does not mean that these variables are not present and are therefore an important

recommendation for further research. Also, in understanding the adoption of green modular innovations future research could take a longitudinal perspective and assess how the proposed adoption paths affect adoption over time. Third, although the findings are based on an extensive literature review and three case studies, additional empirical data is required to generalize the findings. To this end, future research could usefully focus on testing the identified paths and the associated propositions concerning the adoption of innovative modular housing products in a large-scale study. A fourth limitation is that only a single market, namely large-scale housing projects in the affordable (i.e. low-cost) housing segment in the Netherlands, has been studied. Future studies could extend the research to other market segments and to housing projects in other countries and use cross-national data to account for differences in institutional structures. This also includes assessing the identified paths relative to how adoption decision making take place, as well as the implications of adoption decisions for design and construction processes. Finally, future research might focus on the environmental impact of adopting green modular innovation. Going beyond the desire to reduce the environmental impact, a key driver of adopting modular innovation in the housing sector is to improve productivity and increase the level of industrialization. However, it is yet unclear, what the environmental impact is of modular innovation in terms of natural resource consumption and pollutant emissions. To close this gap in knowledge, it is recommended to assess this environmental impact by applying the Bounded-adjusted Measure (BAM), as suggested by Miao et al. (2021).

From academic, managerial and policy perspectives, addressing the research opportunities described above could make important contributions to the understanding of both the adoption and implications of green modular innovation.

CRediT authorship contribution statement

Johannes A.W.H. van Oorschot: Conceptualization, Writing – original draft. **Johannes I.M. Halman:** Conceptualization, Writing – original draft. **Erwin Hofman:** Conceptualization, Writing – original draft. All three authors have contributed in conceptualizing and conducting the research and in writing the paper. The order of the authors reflects the relative contribution of the first author in writing and revising the paper. The second and third author have equally contributed and are in an alphabetical order.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

We thank the anonymous reviewers whose valuable comments have helped us to improve this manuscript. The authors would also like to thank Rudolph Jauregui Becker for his valuable work during collecting and analysing the data.

Supplementary data. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2021.128524>.

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