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# Synergies between Mass Customisation and Construction 4.0 Technologies

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**Abstract:** A challenge faced by some companies in the residential building sector is to cope with the complexity introduced to respond to the increasing diversity of customer demands in a profitable and sustainable way. Mass customisation (MC) has been described as a strategy to deliver customised products at costs and delivery times similar to mass production. The implementation of this strategy can be supported by several information and communication technologies emerging in the Industry 4.0 paradigm, which has been named Construction 4.0 in the construction industry. The aim of this research work is to identify the synergistic potential between Construction 4.0 technologies and the implementation of MC practices in the construction sector. A decision matrix associating a set of MC practices and C4.0 technologies has been devised based on a literature review. Specialists assessed the relationships between items, and the Jaccard similarity index was calculated to understand which Construction 4.0 technologies should be jointly implemented to support MC strategies. As a secondary contribution, this study has also proposed a method to guide companies in the identification of technologies that can support the implementation of MC in specific contexts.

**Keywords:** mass customisation; industry 4.0; construction 4.0; synergy; technologies



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## 1. Introduction

Mass customisation (MC) is a strategy for delivering products and services that meet the individual needs of different customers with product costs or delivery times that are similar to mass production [1–4]. MC aims to provide superior value [5] by focusing on customers, regarded as active players in value generation [6]. However, delivering customised and innovative products requires flexible systems and structures capable of handling increased complexity, which can be achieved by implementing innovative digital technologies [7].

The interest on the application of MC in the construction industry, especially in housing, has grown, due to the dissemination of modular construction [8], and also to the dissemination of digital technologies that have contributed to increase the flexibility of production systems in industry, under the paradigm named Industry 4.0 (I4.0) [9].

I4.0 refers to the technical integration of cyber-physical systems (CPS) into manufacturing and logistics, as well as the use of the internet of things (IoT) and services (IoS) in industrial operations. In this new paradigm, a wide range of emerging technologies is used to enhance processes throughout their life cycle, allowing the interconnection of all their processes, agents, and products [9]. I4.0 has opened up new possibilities for manufacturing systems by proposing adjustments to traditional business models [9], value creation, downstream services, and work organisation [10]. It provides solutions to industry fragmentation [7] by allowing a new level of socio-technical interaction among all actors and resources involved in manufacturing [10]. The increasing levels of integration, connectivity, and real-time collaboration create opportunities for meeting the demand for customised and sustainable products [7], incorporating customer and product requirements into various stages of the product development process [10].

In the construction industry, Construction 4.0 (C4.0) was proposed as a contextualised version of I4.0. According to Osterreich and Teuteberg [11], the construction industry can potentially be transformed into a technology-driven industry, based on a wide range of technologies that enable digitisation, automation, and integration of processes at different stages in the supply chain, including building information modelling (BIM), cloud computing, and IoT. Construction quality and productivity are expected to improve due to C4.0's ability to partially automate design and manufacturing processes and the capability of handling a large amount of diverse data [12].

According to Gandhi et al. [13], using I4.0 technologies to support MC can create new opportunities for delivering products and services. The literature points out synergies between both approaches. I4.0 technologies can potentially contribute to extending the ability to respond flexibly [10] so that customers' [7,10,11,13] and suppliers' demands can be met, providing opportunities for attractive growth and margins [7,13]. In the construction industry, this can lead to the development and delivery of customised projects [9] while maintaining profitability [7] and improving construction quality and productivity [12]. Moreover, these technologies can provide more process transparency, improving decision-making [10].

However, the adoption of C4.0 technologies in the construction industry is still relatively slow due to some inherent characteristics of this sector: unique products, fragmented supply chain, slow process improvement, and lack of strategic alignment between stakeholders [12,14]. Moreover, the benefits of applying those technologies in the sector are confronted with financial, economic, and feasibility challenges [15] and little awareness of the technologies in this sector [16]. Despite the availability of C4.0 technologies, decision-makers face challenges regarding their selection and prioritisation. Maskuriy et al. [12] suggest developing studies on strategies for implementing I4.0 in the construction industry.

Considering the context described above, the following research questions arise: (i) What is the synergistic potential of C4.0 technologies for enabling the implementation of MC practices? (ii) Which C4.0 technologies have the potential to be jointly implemented to support the implementation of MC strategies? Therefore, the aim of this research work is to identify the synergistic potential between Construction 4.0 technologies and the implementation of MC practices in the construction sector. It is expected that those technologies can support the adoption of an MC strategy in handling the additional complexity of delivering customised products. Another outcome of this investigation is a method to guide companies in the identification of technologies to support the implementation of MC in specific contexts.

A decision matrix containing a set of MC practices and technologies was devised based on a literature review. The relationships between the matrix items were assessed in a workshop with specialists on MC and digital technologies. This resulted in a ranking of synergies, indicating the technologies' potential to enable the implementation of MC strategies. Moreover, the Jaccard similarity index was calculated to assess the similarity of use and co-dependency between different technologies. This index identifies which technologies have the potential to be jointly implemented as they were concomitantly cited in the matrix regarding a given practice.

This investigation has an exploratory character, considering that only five specialists with academic or practical experience were involved in assessing the synergies. The small sample was considered sufficient for devising and assessing the proposed method, but the results cannot be generalised. The synergies between items may change depending on the context and the selection of specialists to assess the matrix. The discussions in the workshops also pointed out some knowledge gaps regarding specific relationships.

## 2. Literature Review

### *2.1. Mass Customisation*

According to Da Silveira et al. [4], the success of MC depends on several internal and external factors, including customers' demand for variety, the degree of readiness of the supply chain, the availability of technology, and whether knowledge is shared among stakeholders. Moreover, MC implementation strategies rely on the promotion of continuous improvement, organisational and individual learning, and dissemination of practices within the company [17].

Therefore, the success of an MC strategy depends on the coordinated efforts from three different areas of the company: customer integration, product design and operations management [18,19]. Customer integration is concerned with understanding and modelling different customer requirements, aiming to improve value generation [19,20]. Kumar et al. [21] suggest that it can be achieved by co-design and other types of interactions, including configurators, and elicitation of needs.

Based on customer requirements, product alternatives are developed by translating requirements into design specifications. Those alternatives must define the degree of customisation to be implemented in different stages of construction projects (e.g., design, production, or after delivery) [18]. Finally, operations management is concerned with producing and delivering customised goods by managing production and the supply chain to keep costs and delivery times acceptable. Moreover, the definition of a MC strategy should start by making some core decisions related to the scope of MC and then move to those three areas [18]. According to Hentschke et al. [18], it is noteworthy that information exchange and knowledge dissemination are critical in the interfaces between those three areas.

Several MC practices have been reported in the literature, and these can be related to the four decision categories presented above: core categories, customer integration, product design, and operations management. Practices can be described as tools or techniques implemented to improve performance or solve problems in real-world situations [22]. According to Gherardi [23], the change of practices takes place continuously due to its intrinsic dynamic of innovation and constant refinement. In this study, 31 practices were identified and described (Table 1). These practices provide a broad view of the MC and can be combined to devise suitable MC strategies for different contexts [18]. The fourth column specifies a short name for each practice in order to make it easy the understanding of the decision matrix.

**Table 1.** MC Practices.

| Decision Categories | Code | Practice | Short Name | Based on |
|---|---|---|---|---|
| Core Categories | $P_1$ | Identify customisable items of greater value-added capabilities | Value items | [4,24,25] |
| | $P_2$ | Offer innovative customisation units, such as those related to sustainability and automation | Innovative options | [18,26] |
| | $P_3$ | Adopt methods for identifying the demand for customisation, consumers preferences, and market segmentation to define solution spaces | Customisation demand | [4,18,24,27,28] |
| | $P_4$ | Define a limited solution space to achieve economies of scale | Limited solution space | [18,27,29–32] |
| | $P_5$ | Define different levels of customisation with specific customisation units according to customers' preferences, distinct market segments, and projects | Customisation levels | [18,28,33] |
| | $P_6$ | Use product prototyping to test and communicate technical and design solutions to stakeholders | Product prototyping | [18,34,35] |
| | $P_7$ | Create a database of customers orders for customising housing units shared within departments | Orders database | [4,18,24,25,27] |
| | $P_8$ | Use specialised information systems for managing production management of customised products | Information systems | [18,35–37] |
| | $P_9$ | Use choice menus as a learning tool, to understand customers' needs and preferences and provide feedback to new product development | Choice menu learnings | [18,37] |
| | $P_{10}$ | Manage information about customisation orders to create knowledge for the company | Knowledge creation | [18,26,27,30,33] |
| | $P_{11}$ | Create metrics that can be used to analyse the trade-offs between flexibility–productivity | Trade-offs metrics | [18,27,38] |
| | $P_{12}$ | Develop and refine products in partnership with the supply chain | Supply chain partnership | [4,35,39] |

**Table 1.** *Cont.*

| Decision Categories | Code | Practice | Short Name | Based on |
|---|---|---|---|---|
| Customer integration | $P_{13}$ | Adopt information technology tools, choice menus, or online configurator systems to support customers' choice and product configuration | Support customers | [18,25,31,36,40–42] |
| | $P_{14}$ | Build physical or virtual prototypes, virtual or augmented reality, or showrooms for showing the product alternatives | Product alternatives | [18,25,39,43] |
| | $P_{15}$ | Use augmented, virtual, or mixed reality to present product alternatives to customers | Present options | [44,45] |
| | $P_{16}$ | Prepare the relational context, including training employees for technical assistance during the customer's decision-making process | Relational context | [43,44,46] |
| | $P_{17}$ | Use tools, lists, and databases that communicate additional costs and suppliers' information for customisation to support customer decision-making during configuration, enabling negotiation and increasing transparency | Additional costs | [3,18,31,35,42,44] |
| | $P_{18}$ | Monitor customers' buying experience to feedback on the process | Buying experience | [44] |
| | $P_{19}$ | Define interactions with customers and display them in a customer journey representation | Customers interaction | [18,25,40,42,47] |
| | $P_{20}$ | Prepare customers for decision-making process | Decision-process | [25,44] |
| Product Design | $P_{21}$ | Use modular components that allow product variations according to customers' requirements | Modular components | [18,31,32,38,40] |
| | $P_{22}$ | Offer customisation options according to the execution stage of the work | Phased options | [29,33,35] |
| | $P_{23}$ | Offer additional customisation units after occupancy or replace previously chosen components according to customers emerging needs | Post-occupancy offers | [18,25,26] |
| | $P_{24}$ | Use standardisation methods for (communalisation) | Standardisation | [25,48] |
| Operations management | $P_{25}$ | Translate customers' requests for design and production instructions | Production instructions | [4,25] |
| | $P_{26}$ | Build a prototype or a model apartment to guide the execution of works' team and enable continuous improvement | Guiding prototype | [34,35] |
| | $P_{27}$ | Define customisation levels according to the decoupling point in long-term planning | Decoupling points | [33,35,39] |
| | $P_{28}$ | Processes that allow customisation postponement | Customisation postponement | [27,35,39] |
| | $P_{29}$ | Automation in the production of components | Automation | [26,35] |
| | $P_{30}$ | More flexible production arrangements to contribute to the production of custom items | Flexible production | [3,25] |
| | $P_{31}$ | Industrialisation or prefabrication of components for production in short lead times | Short lead times | [35] |

Solution space is a key decision in MC [49] and one of the underlying concepts strongly related to several practices in Table 1. It determines the set of customisation options defined by the company to be offered to customers [2], i.e., what will and will not be offered, establishing the set of options offered [50]. It must be based on identifying customers' demands, especially related to product attributes [49]. The diversity of options must not exceed the organization's capacity, as too much variability can increase the complexity of the production system [51]. The solution space provides the information required for the product configuration, which is held through an adequate system for customer involvement [20]. The integration of the customer into the configuration of an individual solution must be made through a company–customer interaction [52] that involves different ways of presenting the solution space. The effectiveness of transferring this information between the customer and the company largely determines the success of MC [53].

Customer involvement in product design may occur at different levels positioned in a continuum between standardisation and customisation poles [4,29,54,55]. This continuum is characterized by two distinct strengths: aggregation and individualization [29], or productivity and flexibility [55]. It is a trade-off between the flexibility desired by customers and the productivity desired by companies. Each company will position the MC strategy according to its specific applications and contexts [29]. In this continuum, the customer-order decoupling point (CODP) defines the moment when customers can influence the design and manufacturing of customised products [56]. This point establishes the part of the supply chain in which the product is predicted and the part from which it allows adaptations according to the customer's choice [57].

### *2.2. C4.0 Areas and Technologies*

Considering the categories proposed by Oesterreich and Teuteberg [11], Muñoz-La Rivera et al. [9], Maskuriy et al. [12], and Sawhney et al. [58], C4.0 technologies can be grouped into three main areas: physical domain, simulation and modelling and digitalisation and virtualisation. The digital layer and digital tools group, proposed by [58], have been subdivided between the simulation and modelling, and digitalisation and virtualisation areas [11]. Several technologies associated with these areas have been reported in the literature. In this study, 19 have been identified as relevant for MC, and classified under those three categories (Table 2).

**Table 2.** C4.0 Technologies.

| Area | Code | Technology | Description |
|---|---|---|---|
| Physical Domain | $T_1$ | Internet of Things (IoT)/Internet of Services (IoS) | Connects digital BIM models with physical devices for on-site control and monitoring, optimising communication, and construction logistics in general [9] |
| | $T_2$ | Modular Construction | A system's capacity to be subdivided into smaller, independent modules (subsystems), linked and assembled using standardised rules [9] |
| | $T_3$ | Prefabrication/Offsite construction | Practice of producing construction components in a manufacturing factory, transporting them to construction sites, and assembling them to construct buildings [59] |
| | $T_4$ | Additive Manufacturing | The additive process of depositing successive thin layers of material upon each other, producing a final three-dimensional product through a wide variety of materials [60] |
| | $T_5$ | Robotics and automation | Machines that can be programmed to interact autonomously with objects to perform tasks of different kinds [9] |
| | $T_6$ | Cyber-Physical Systems (CPS)/Embedded systems | Ecosystem that entangles the network and physical worlds through real-time communication and cooperation between value network participants such as devices, systems, organisations, and people [61] |
| | $T_7$ | Product-Lifecycle-Management (PLM) | Deals with the integration of all information produced throughout all phases of the whole lifecycle of a company's product (Sudarsan et al., 2005) through integrated IT solutions, involving customers, suppliers, and resources [9] |
| | $T_8$ | Human–Computer Interaction (HCI) | Studies the interaction between humans and computers in all forms, and engaged with understanding the relationship between humans and emerging technologies [62] |
| | $T_9$ | Radio-Frequency identification (RFID)/ Sensors/Worker sensors | Use of electromagnetic fields, radio frequency waves, to automatically detect, identify, geolocate, and track tags affixed to objects [9] |
| Simulation and Modelling | $T_{10}$ | Building information modelling (BIM) | Tools, processes and technologies that are facilitated by digital, machine-readable documentation about a building, its performance, its planning, its construction and its operation [63] |
| | $T_{11}$ | Simulations models and tools | Replicate and thus predict the behaviour of systems and processes, i.e., analyse structures during the design phase, predict energy consumption, simulate fire evacuations [9] |
| | $T_{12}$ | Augmented/Virtual/Mixed Reality (AR/VR/MR) | AR creates connections between the physical world and digital information by providing an immediate, simple interface to a digitally enhanced physical world (Schmalstieg and Hollerer, 2016). VR generates a view that appears to the user's senses similar to the real world through a computer simulation [64] |
| | $T_{13}$ | Predictive maintenance | Use simulations or early detection of key indicators to predict future failures in installations, systems, or equipment [9] |
| | $T_{14}$ | Neural Networks | Computational models inspired by biological neural networks that use interconnected nodes that process information to generate automatic predictions and learning [9] |
| | $T_{15}$ | Digital Twin | Virtual replica of a physical system that allows different simulation disciplines characterised by the synchronisation between the virtual and actual system [9] |

**Table 2.** *Cont.*

| Area | Code | Technology | Description |
|---|---|---|---|
| Digitalisation and Virtualisation | $T_{16}$ | Big data and analytics | Concerned with the understanding of the big data, provides insights to transform companies through data-driven decision-making [65] |
| | $T_{17}$ | Mobile Computing and Applications | Use of mobile devices to support communication and collaboration during the construction process [11] |
| | $T_{18}$ | Social Media | Used as a platform for collaboration, interactions, and information sharing among the different project participants [11] |
| | $T_{19}$ | Data Sharing | Sharing of data between stakeholders for cooperative purposes [66] |

The physical domain area refers to the digital end-to-end engineering integration, including technologies to automate the physical manufacturing environment [9], which can be used to create the idea of a smart factory for the construction environment [11]. The following technologies can be included in the physical domain (Table 2): IoT/ IoS, modular construction, prefabrication/offsite construction, additive manufacturing, robotics and automation, CPS/embedded systems, product-lifecycle-management, human–computer interaction, radio-frequency identification/sensors/worker sensors. According to Muñoz-La Rivera et al. [9], these technologies make it possible to take or receive data from physical artefacts, manage them or execute actions in the real environment.

The simulation and modelling area includes tools for data processing and producing in-depth knowledge on the expected behaviour of products and processes at different stages of the construction projects e.g., design, construction, and operation of buildings and infrastructures [9]. The technologies from this area include (Table 2): BIM, simulation models and tools, AR/VR/MR, predictive maintenance, neural networks, and digital twins. These can be used to deal with the high degree of complexity of some construction projects by improving an operations design [11].

Finally, the digitalisation and virtualisation area is concerned with integrating services, collaboration platforms, support of communication and collaboration, and collection and accessibility of data [11]. This area includes (Table 2): big data and analytics, mobile computing and applications, social media, and data sharing. These technologies deal with the storage, maintenance, and transfer of data safely and efficiently.

Each C4.0 technology may influence or depend on others, and their joint implementation is often required [7]. Consequently, several studies have emphasised the potential of using data-integrated technologies to enhance others, i.e., [65,67,68]. The combined use of technologies potentially allows the development of collaborative, synchronised systems to automate design and construction processes and handle large amounts of diverse data [12].

## 3. Research Method

Design science research (DSR) is the methodological approach adopted in this investigation. This approach has a prescriptive character, seeking to devise solution concepts, named artefacts, to solve classes of problems [69]. The main outcomes of this investigation are the proposed method and the instantiation of that method in a specific context. As mentioned above, the investigation of the synergistic potential between C4.0 technologies and the implementation of MC practices has an exploratory character, as it was based on the perception of five specialists.

Figure 1 provides an overview of the research design, including the research questions, the sources of evidence, and the steps of the research method. A literature review was carried out to define a set of MC practices and a list of potential C4.0 technologies. The items were selected, categorised and distributed in a decision matrix to assess the synergistic potential between pairs through a workshop with specialists. Afterwards, the technologies that can be implemented together were identified through the Jaccard similarity index. The following subsections present a detailed description of each stage.

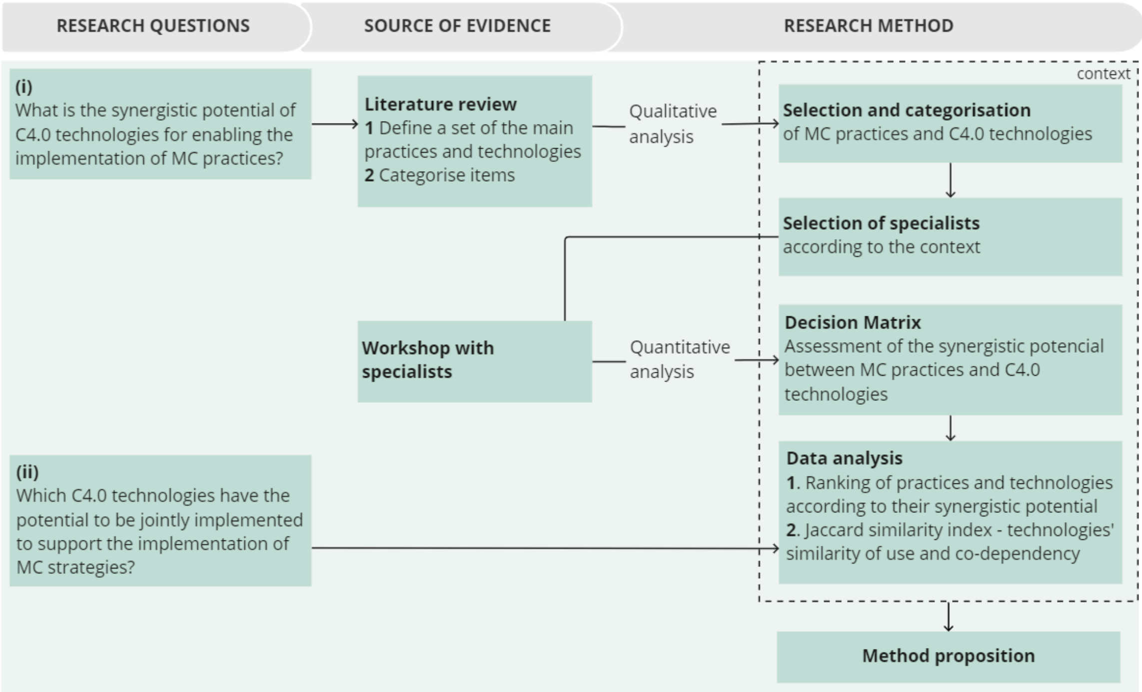


**Figure 1.** Research design.

### 3.1. Selection and Categorisation of MC Practices and C4.0 Technologies

The literature review for selecting MC practices and C4.0 technologies was based on papers from 2010 onwards. The snowballing technique was undertaken to complement the review, including papers from 1996 onwards in the case of an MC strategy. The keyword search included "construction", "house-building", "residential", "customisation", "mass customisation", "mass customisation practices", "industry 4.0", "construction 4.0", "technologies", and "synergy". From this search, 32 papers were selected. As a result, two sets of items were identified, one related to the MC strategy and its practices and the other to C4.0 technologies. In total, 31 practices and 19 technologies were grouped by similarity and classified in the areas and decision categories suggested by the literature and discussed in Tables 1–3. Other practices can be included in future studies as they change continuously due to their intrinsic dynamic of innovation [23].

**Table 3.** Specialists' description.

| Specialist | Background | Education | Area of Expertise | Years in Industry | Years in Academia |
|---|---|---|---|---|---|
| 1 | Civil Engineer | PhD | CM, MC | 3 | 38 |
| 2 | Architect and Urbanist | PhD | MC | - | 16 |
| 3 | Civil Engineer | PhD Candidate | DT, CM | 14 | 12 |
| 4 | Architect and Urbanist | PhD | MC, CM | - | 10 |
| 5 | Civil Engineer | PhD Candidate | DT, CM | 9 | 7 |

### 3.2. Selection of Specialists

The selection of the specialists involved in assessing the synergistic potential between MC practices and C4.0 technologies was based on their academic background or practical experience in at least one of those two fields of knowledge. Due to the complementary background of the specialists, the decision was made to run workshops, rather than doing a survey, in order to have discussions to reach a consensual score or to identify knowledge gaps regarding some items or interactions.

The specialists selected for this study had at least 9 years of experience in MC, digital technologies (DT), and construction management. Their previous experience was mainly in the residential building sector of the construction industry in Brazil. In this country, most projects adopt traditional construction methods, and the use of I4.0 digital technologies was still in the early stages. The choice of the specialists was based on the need for a group of people that had knowledge of both MC and DT, capable of articulating those topics on a broad basis.

Specialist 1 (Table 3) was a full professor that developed research on construction management and MC, including more than 140 relevant publications. A large share of those publications was based on studies developed in partnership with companies from the construction sector. Specialist 2 was a professor with 16 years of academic experience, with 12 relevant publications, most of them on MC. Specialist 3 was a consultant and a PhD candidate who had been involved in implementing different DT for construction management. Specialist 4 had an academic background of 10 years and had 6 relevant publications on the application of MC in housing, which were based on research developed in close collaboration with construction companies. Specialist 5 was a PhD candidate in the area of DT and innovation and a founding member of a construction management consultancy company that operates in several industrial segments, including construction.

### *3.3. Decision Matrix Associating MC Practices and C4.0 Technologies*

The practices ($P$) and technologies ($T$) selected in the literature review were disposed of in rows and columns of a matrix, respectively, as shown in Figure 2. $S_{ij}$ indicates the measure of synergy between the $P_i$ practice and the $T_j$ technology, where $I = 1, 2, \ldots P$, and $j = 1,2, \ldots T$. In this case, $P$ indicates the number of practices ($P = 31$), and $T$ the number of technologies ($T = 19$) in the matrix. A geometric scale (1, 3, and 9) was adopted to establish priorities for the most critical relationships. In this case, empty cells means no relation, 1 means a weak relationship, 3 is a moderate relationship, and 9 is a strong relationship [70].

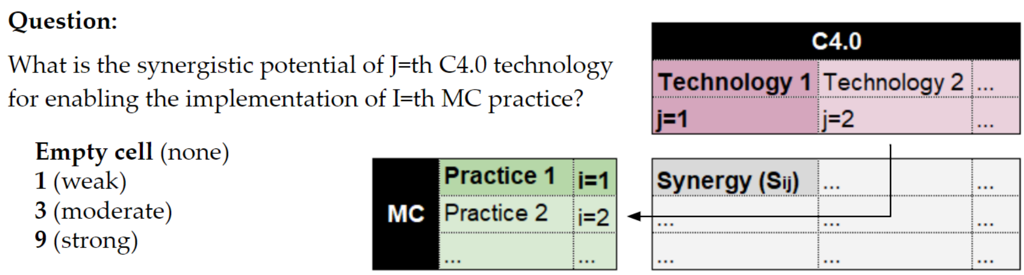


**Figure 2.** Decision matrix structure indicates the measure of synergy between practices ($P_i$) and technologies ($T_j$).

The workshop with the specialists, mentioned in Section 3.2, was conducted in three stages in order to analyse all pairs of practices and technologies. The participants had to indicate according to the scale if a given technology $T_j$ could enable the implementation of a given practice $P_i$. Then, a score for each matrix's cell was established. The workshop was facilitated by the authors of this paper. An important limitation of this investigation was that the specialists considered the context of the Brazilian housing industry.

The first stage of the workshop was carried out in a 2 h online meeting. Two activities were undertaken with the specialists. Initially, the list was assessed regarding the completeness of the set of items. Then, the specialists carried out a shared assessment with the purpose of training and standardising their understanding of filling out the matrix. Then, they discussed and assigned a consensual score for each cell. The specialists undertook the second stage individually with the cells that were not discussed in the first run. This assessment resulted in five correspondence matrices. According to them, the filling time was about five hours. From that, a final matrix was obtained from a geometric mean of the scores given by the specialists. The third stage of the workshop was a second 2 h online meeting with the specialists. The aim was to evaluate the scores with significant differences, seeking to reach a consensual assessment. The result was a decision matrix with the scores representing the synergistic potential metric between each practice and technology.

### 3.4. Data Analysis

The decision matrix with the final scores was the basis for performing the two steps of data analysis: (i) ranking of items according to the synergistic potential between MC practices with all technologies and between C4.0 technologies with all practices, answering to RQ–1; and (ii) applying the Jaccard similarity index, to identify technologies that have potential to be jointly implemented to support the operationalisation of an MC strategy, answering to RQ-2.

#### 3.4.1. Ranking of Practices and Technologies

The procedure to rank the items' global synergy metric had two steps (Figure 3). Firstly, the sum of the synergy scores (Equation (1), $W_{i.} = S_{i1} + S_{i2} + \ldots S_{iT}$) and columns (Equation (2), $W_{.j} = S_{1j} + S_{2j} + \ldots S_{Pj}$) from the decision matrix was carried out. This resulted in marginal rates of practices ($i$) and technologies ($j$), representing its global synergies metric ($W_{i.}$, $W_{.j}$). Then, the global synergies' metrics were ordered according to their synergistic potential ($W_{.j}$ and $W_{i.}$), that is, the contribution of the *J-th* technology independently of the practice and the contribution of the *P-th* practice independently of the technology. The higher the $W_{.j}$, the higher the synergistic potential of that technology to enable the implementation of the MC set of practices. Moreover, the higher the $W_{i.}$, the higher the synergistic potential of that practice to be enabled by the C4.0 technologies.

$$W_{i.} = \sum_{j=1}^{T} S_{i.} \tag{1}$$

where:

| | |
|---|---|
| $T$ : | Technology |
| $S_{i.}$ : | Synergy scores between *P-th* practice |
| $W_{i.}$ : | Global synergies metrics of practices |

$$W_{.j} = \sum_{i=1}^{P} S_{.j} \tag{2}$$

where:

| | |
|---|---|
| $P$ : | Practice |
| $S_{.j}$ : | Synergy scores between *J-th* technology |
| $W_{.j}$ : | Global synergies metrics of technologies |

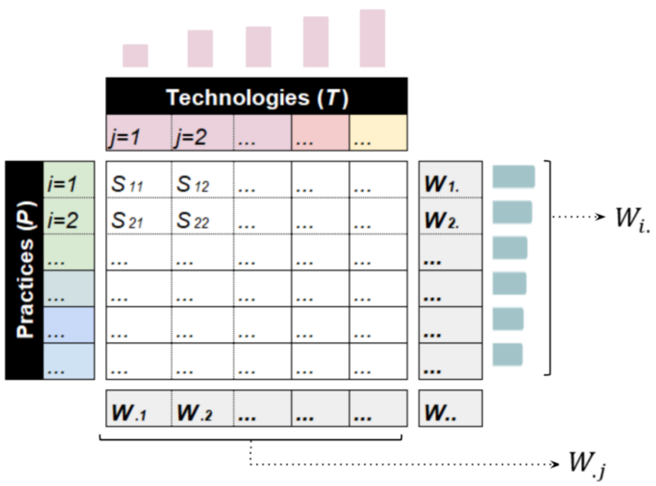


**Figure 3.** Ranking of the global synergies metric.

The scores were normalised from 0 to 100%. In order to assess the impact of each practice ($i$) and technology ($j$) in the marginals, a relative measure was calculated between the sum of the row and column concerning the maximum possible value (Figure 4). The maximum possible value means the hypothetical situation in which all items from a column ($W_{.j}$) or a row ($W_{i.}$) were assessed with a score 9, that is, $X_{max}\ S_{i.} = 9 \times T$, where $T = 19$, and $X_{max}\ S_{j.} = 9 \times P$, where $P = 31$. For example, the maximum possible value for $P8$ ($W_{8.}$) is 171, considering all 19 technologies with a strong relationship (score 9). If the sum of the weights in this row ($W_{8.}$) is 67.26, according to the geometric mean of the specialists' assessment, this resulted in 39% synergy over the maximum possible value, $W_{8.} = (67/171) = 0.39$, or 39% (see Figure 4). The darker the colour, the higher the synergy between the items.

| $P_8$ | T1 | T2 | T3 | T4 | T5 | T6 | T7 | T8 | T9 | T10 | T11 | T12 | T13 | T14 | T15 | T16 | T17 | T18 | T19 | $W_{8.}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $X_{max}$ (total possible) | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | **171** |
| Geometric mean (specialists' assessment) | 3,36 | 6,00 | 4,25 | 3,00 | 2,56 | 4,62 | 1,65 | 1,00 | 2,74 | 8,15 | 6,00 | 3,47 | 0,68 | 0,41 | 4,62 | 6,00 | 2,74 | 0,00 | 6,00 | **67,26** |
| Normalised synergy score ($W_{8.}$) | 37% | 67% | 47% | 33% | 28% | 51% | 18% | 11% | 30% | 91% | 67% | 39% | 8% | 5% | 51% | 67% | 30% | 0% | 67% | **39%** |

**Figure 4.** Impact of practice $P(i = 8)$ and technology ($j$) in the marginals.

#### 3.4.2. Jaccard Similarity Index

Jaccard similarity index [71] was applied to represent the technologies' similarity of use, indicating pairs that may be jointly implemented. Firstly, the decision matrix with the scores representing the synergies ($S_{ij}$) was converted to binary scores. For instance, the scores were converted to 0, if $S_{ij} < 3$ and 1 otherwise. Afterwards, the Jaccard Index was calculated using R Software®. The Jaccard index is given by the ratio between the number of times that pairs of technologies were concomitantly cited and the total number of times that at least one of them was cited (Equation (3)). The final indexes vary from 0 to 1, in which 1 represents the highest similarity of use and co-dependency between the two technologies.

$$J(\ T_i; T_{i+1}) = \frac{|T_i \cap ; T_{i+1}|}{|T_i \cup ; T_{i+1}|} \tag{3}$$

where:

$T_i$ : Technology $i$
$T_{i+1}$ : Technology $i + 1$
$J(\ T_i; T_{i+1})$ : Jaccard similarity index for the technologies $T_i; T_{i+1}$

For example, "Modular Construction" ($T_2$) and "Building Information Modelling" ($T_{10}$) showed a Jaccard index or level of similarity of use of 0.68 on a scale from 0 to 1. $J(T_2, T_{10}) = 0.68$ indicates that $T_2$ and $T_{10}$ applications were concomitantly cited in the matrix regarding the implementation of the practices; that is, they are highly connected and recommended to be used in combination for the implementation of an MC strategy.

### *3.5. Overview of the Method to Identify the Synergistic Potential between MC and C4.0*

After carrying out the four steps described in the research method, the researchers analysed and reflected on the results achieved. Based on that, a simplified version of the research method was devised to be used by companies interested in choosing C4.0 technologies to support the implementation of MC strategies. For example, companies can use other means to choose MC practices and C4.0 technologies to be considered rather than making an extensive selection of items based on a literature review. In fact, each company can select a set of technologies and practices that are applicable in their specific context.

Finally, an assessment of the method in terms of utility and applicability was carried out. The evaluation of the utility was based on the type of outcome produced by the method: (i) establishing a ranking of C4.0 technologies to support MC strategies; and (ii) identifying technologies that can be used in combination according to their similarity of use. The evaluation of the applicability was concerned with the ease of use of the method, and also whether it can be used to assess the synergies between MC and C4.0 technologies in specific contexts. A limitation was that as the method emerged at the end of the investigation, only an internal assessment by the research team was undertaken. Therefore, further research is necessary to evaluate and refine the method by implementing it in the context of different construction companies.

## 4. Findings

### *4.1. Ranking of Practices and Technologies According to Their Synergistic Potential*

Figure 5 shows three main information: (i) the ranking of the global synergies' metrics of the MC practices, in the rows; (ii) the ranking of the global synergies' metrics of the C4.0 technologies, in the columns; and (iii) the measure of the synergies, in the cells of the matrix. The darker the colour of the cell, the higher the synergy between the items. The rows and the columns were ordered according to the synergistic potential. The first ten items with the highest synergistic potentials were shown to improve readability.

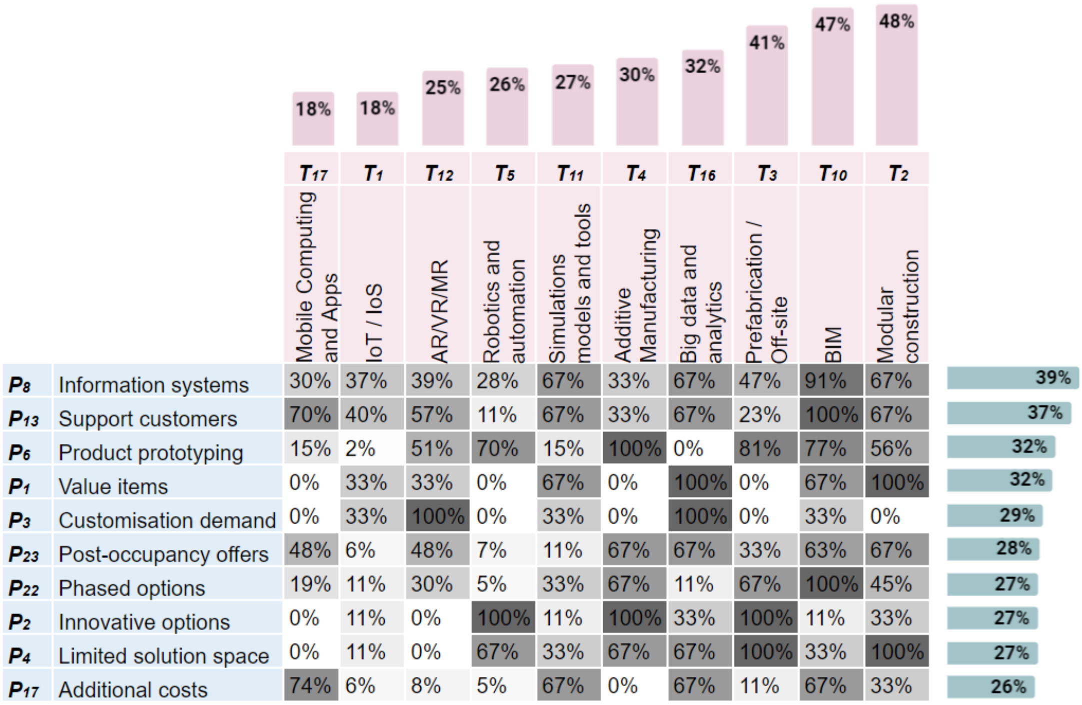


**Figure 5.** Global synergies' metrics between MC practices and C4.0 technologies.

"Use information systems" ($P_8$) had the highest global synergy metric (39%) with all technologies selected for this study. This result means that $P_8$ showed a high potential to be enabled by many technologies discussed in the matrix. Companies face several operational challenges in maintaining product affordability while simultaneously allowing customers to customise their products [37]. As the diversity of choice increases, developers can face rising costs and construction time extensions [72], i.e., in the opposite direction of keeping similar benefits of mass production. Several industries have leveraged the use of information systems to address the challenges related to delivering this variety [18]. In the construction context, although it generates massive amounts of data, the adoption of "Big Data" and its multidisciplinary nature lags behind the progress made in other fields [65,68]. However, there is interest in leveraging such technologies to improve construction process efficiency [65,68]. The high synergy between "Use information systems" and "BIM" (91%) is concerned with the ability to use BIM to provide multidisciplinary information to be processed and used for many purposes, allowing interconnection with many other technologies in the industry [73,74]. The synergy of 91% means that the geometric mean of the scores given by the specialists was 8.146 from a maximum possible of 9 (8.146/9 = 0.905, or 91%). “Modular construction” had 67% synergy, and its ability to handle a system into smaller, independent parts can enable customisation options to be managed and improved with the least disturbances to different items and procedures. In this sense, “Big data and analytics” (67% synergy) potentially help with the identification of patterns, trends, or correlations of interest, while “IoT/IoS” (37% synergy) can support replicating and predicting the behaviour of these processes [9].

“Adopt tools to support customers’ choice” ($P_{13}$) had the second highest global synergy metric. The highlight was “BIM”, with 100% synergy according to the specialists’ assessment, followed by “Mobile Computing and Applications” (70%). The synergy of 100% means that the specialists selected for this study gave the maximum possible score between $P_{13}$ and BIM. Combining these technologies allows customers to experience the solution space variables of cost and time through smartphones, tablets, and augmented reality, facilitating the customisation process [75–78]. However, although 3D modelling provides a more realistic virtual environment, it can cause cognitive difficulties in understanding the models [78]. The buying experience is not limited to an interface or a technology [79]. It includes the physical and relational contexts that make up the customer experience scenario [46,80]. In this scenario, psychological and sensorial aspects must be considered [46], including the interactions between the customers and the technical assistance, associated with loyalty [46] and high levels of satisfaction [81]. Therefore, despite the high synergy between tools such as choice menus and C4.0 technologies ($P_{13}$), the configuration of a customised product should be planned as a buying experience, coordinating all its complementary elements [44].

In the third position, two practices had tied ranks of synergy (32%): “Use prototypes to test solutions” ($P_6$) and “Identify items of value” ($P_1$). Prototypes work as boundary objects for the common understanding of information between stakeholders, increasing transparency, simplifying the number of steps, systematically considering customers’ needs, and assisting continuous improvement [34,35,82]. This process can be enhanced by “Additive Manufacturing” (100% synergy) and “Prefabrication/Offsite construction” (81%) by their potential to allow rapid physical prototyping, while “BIM” (77%) allows real-time information management through a digital prototype. Those prototypes can be used within the company to project compatibilization, to guide labourers about the correct execution on the construction site, and with customers to visualise the customisation options and help them in the decision-making [34]. In contrast with “Prefabrication”, “Additive manufacturing” brings unique capabilities that enable rethinking traditional construction and design methods, such as increasing geometric design capabilities and being more responsive to the on-site and customers’ needs [83,84]. Regarding the interaction between customisation, “Additive Manufacturing” seems particularly suitable for small, highly customised series [85].

The definition of the solution space, one of the fundamental capabilities of MC [49], must be based on existing customer data [39]. In this process, technologies such as “Big data and analytics” and “Social Media” can enable the “Identification of customisable items of greater value-added capabilities” ($P_1$). The use of configuration tools such as choice menus and recommendation systems represents an opportunity to identify and understand customers’ needs and preferences [4,20,86], providing feedback to new product development [18]. The product configuration process allows the companies to access valuable information that can be transformed into explicit knowledge through more accurate product alternatives that better fulfil customers’ needs [20]. The attributes often chosen by customers can be maintained, while the ones rarely demanded can be eliminated [28,49]. Managing this information about customisation orders can be used to create knowledge for the company ($P_{10}$). By contrast, companies can help customers to identify items of greater value to them through recommendation systems or configurators. These tools offer personalised access to information, helping electronic commerce, social media, and other applications in which the volume of information for decision-making is high [87]. The goal is to suggest items that meet customers' needs through a fully automated process, with built-in configuration resources [49] that quickly offer a relevant solution to them [88]. According to Salvador et al. (2009), this represents a paradox: the products are standardised for the company; however, they are visualised as a customised solution for the customer. Stated preference techniques, such as stated choice and menu-based choice, have also been explored in the literature for capturing customers' preferences through data [89,90].

From the technologies' perspective, "Modular construction" ($T_2$) had the highest global synergy metric (48%) with all practices selected for this study. The 100% synergy with five practices from different MC decision categories represents the opportunity to meet future customer demands while simultaneously taking advantage of carrying over technical solutions between projects [91]. The capacity of these systems to be subdivided into smaller, independent modules that are linked and assembled using standardised rules [9] allows the offer of product variations ($P_{21}$) in different execution stages of the work ($P_{22}$). It includes post-occupancy or substituting previously chosen components according to emerging needs through customisation postponement, accommodating late demands ($P_{23}$, $P_{28}$). Despite all these synergies, customisation in traditional construction methods has little support from modularity so far, limiting the advantages of scale [25]. Despite the modular construction acceptability in the market and its potential to solve issues associated with traditional construction practices, a broader adoption is still held back by connected barriers concerning the prefabrication market, the industry's attitude, the process, and the financial hurdle [92]. According to Formoso et al. [39], modularisation can be gradually introduced in construction as the degree of industrialisation increases in the sector [39]. Thus, C4.0 technologies may contribute to further productivity and efficiency improvement as they are part of the nature of offsite construction [93]. Research and development between modular and offsite construction with other C4.0 technologies, such as artificial intelligence and robotics [94], additive manufacturing, BIM, IoT, and AR is still needed to reach their potential benefits [93].

The second (47%) and third (41%) technologies with the highest global synergy metrics were "BIM" ($T_{10}$), and "Prefabrication/Offsite construction" ($T_3$), respectively. BIM plays a key role in terms of linking other technologies [93]. According to Farr et al. [76], BIM can facilitate customisation in construction, providing the information and communications technology platform required for visualising product changes. BIM provides life cycle cost analysis and building performance analysis and allows the evaluation of the environmental, product, and processes impact of decisions regarding construction strategies such as modularisation and prefabrication. This can be associated with the offer of innovative customisation units, such as those related to sustainability and automation ($P_2$). BIM can also support understanding the balance between the flexibility of prefabricated products and modularity at the early building design stages [36]. This is achieved through a test environment used to explore and understand design configurations, engineering, production, and assembly, as well as envisioning a way to organise a configurator interface for the architectural design of industrialised building platforms [36].

### *4.2. Jaccard Similarity Index–Technologies' Similarity of Use*

Figure 6 provides the results of the Jaccard similarity index analysis. Each cell represents the crossing of a given technology with all technologies selected for this study. The darker the blue, the higher the similarity of use and co-dependency between the two technologies from an index that vary from 0 to 1. "Prefabrication/Offsite construction", "Modular Construction", "BIM", and "Additive Manufacturing" had the highest indexes of similarity of use (Figure 6). "Big data and analytics" maintained high index values concerning most technologies, indicating a potential to support the implementation of other technologies in the physical and planning domains. The low indexes of "Human–Computer interaction" ($T_8$), "Radio-Frequency Identification/Sensors" ($T_9$), and "Predictive maintenance" ($T_{13}$), with all technologies indicating that they are still poorly considered in the construction context.

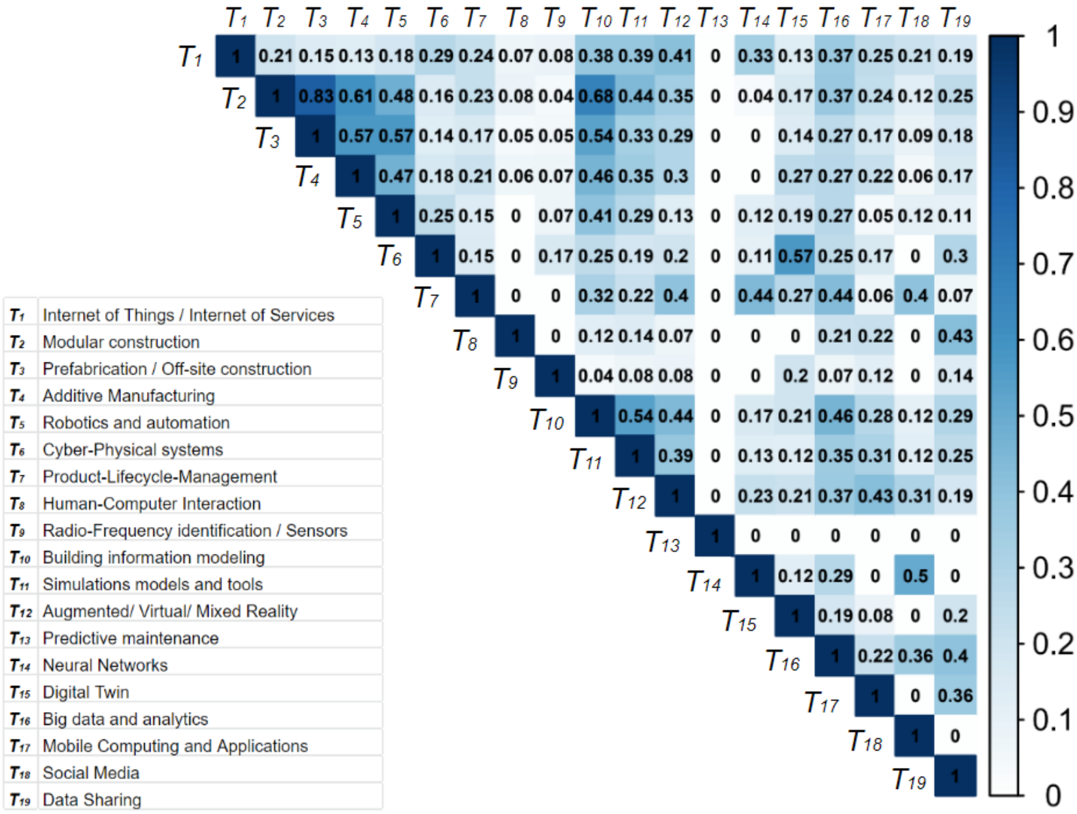


**Figure 6.** C4.0 technologies' similarity of use and co-dependency in an MC strategy.

### 4.3. Method to Identify the Synergistic Potential between MC and C4.0

Figure 7 provides an overview of the proposed method, which is divided into six phases. This method is meant to be applied in a well-defined context, so that it can be effectively used to support the development of MC strategies.


**Figure 7.** Overview of the proposed method.

The MC practices and C4.0 technologies proposed by this paper can be used by companies as a basis to select items that are applicable to their specific contexts or projects (Phase 1). Updating or extending this list of practices and technologies in future replications of this method may be necessary due to their intrinsic dynamic of innovation. The outcome of this phase is a set of items appropriate to the needs, capabilities, and challenges of the company regarding the implementation of MC strategies.

Phase 2 consists of selecting specialists to assess the synergistic potential between practices and technologies. The group may have an academic background or practical experience in at least one of the fields, being capable of articulating the topics according to the companies' needs. This step is fundamental since the results are based on the scores given by the specialists.

In Phase 3, the items selected in Phase 1 are disposed of in a decision matrix. MC practices are positioned in rows (i) and C4.0 technologies are in columns (j). It is suggested to set a code and a short name for each item in order to make it easy the understanding of the decision matrix. The full description of practices and technologies can be provided as complementary material for supporting the discussions.

The synergistic potential between the items disposed of in the decision matrix is assessed through a workshop with the selected specialists (Phase 4). The workshop can be face-to-face or virtual. The workshop facilitator should have at least a basic knowledge of MC and C4.0 fields and a deep understanding of the needs and challenges of the company regarding the implementation of MC practices. According to a geometric scale (1, 3, and 9), the participants should indicate the synergistic potential of a technology *Tj* to enable the implementation of a given practice *Pi*. Then, a score for each matrix's cell is established. The following question should be done in every crossing between a row (*I*) and a column (*J*): "What is the synergistic potential of *J* = *th* C4.0 technology for enabling the implementation of *I* = *th* MC practice?" The facilitator should foster the discussion between specialists with different, complementary backgrounds to reach a consensual score for each cell. The scores are based on a geometric scale (1, 3, and 9) [70]. The workshop duration will depend on the number of items selected in Phase 1, but it is expected to be necessary around two stages of 2 h.

In Phase 5, the scores given by the specialists in the decision matrix are used to assess the ranking of the synergistic potential between items. This ranking is a simple application of Equations (1) and (2) (Item 3.4.1) in a spreadsheet. The scores can be normalised from 0 to 100% in order to make it easy the understanding. In Phase 6, data from the decision matrix is analysed by calculating the Jaccard similarity index. First, the scores must be converted into binary scores (0, 1), where 0 if $S_{ij} < 3$ and 1 otherwise. Then, the Jaccard Index is calculated using Equation (3) (Item 3.4.2). Results from this phase can help companies to identify technologies with the potential to be jointly implemented.

## 5. Discussion

The main contribution of this investigation, in comparison to the results of previous studies that have addressed the use of C4.0 technologies to support MC, is that the proposed method adopts a broad perspective of MC, not limited to specific practices, such as choice menu or visualisation techniques. Therefore, synergies have been identified between a set of technologies and a set of MC practices, instead of one-to-one relationships.

Regarding the results for the specific context considered, MC practices have shown a high synergy with modular construction, including different decision categories, from the solution space definition (core categories) to decisions regarding the flexibility of the production system (operations management) and the availability of options according to the construction stage (product design). Modular construction and prefabrication/offsite construction showed the highest similarity of use in the Jaccard index analysis between all technologies. This result is supported by the literature: modular, offsite construction and prefabrication are often pointed out as complementary approaches [8,91,92,95,96]. Another insight from the application of the method is the high similarity of use for BIM, simulation and modelling tools, and big data and automation. These applications have the potential to support an MC strategy to achieve flexibility, customisation postponement, interchangeability of parts, and economy of scale through repetition. Despite this potential, more research is needed on using C4.0 technologies for offsite and modular construction [93,94].

The majority of C4.0 technologies and practices can be leveraged by better use of the potential sources of big data [65], including the challenges related to the delivery of variety [18]. Data management is the core of crucial decisions in an MC strategy, such as some of the practices selected for this study: understanding the current and future needs of customers, analysing trade-offs between flexibility and productivity to achieve economies of scale, managing production, providing feedback to new product development, creating knowledge for the company, among others. A major challenge is dealing with the fragmented data management practices in the construction industry and the low quality of datasets [65].

The findings of this exploratory study reinforce the relevance given by the literature to BIM as having a central role in linking product and process models to other technologies. BIM had one of the highest potentials among all technologies for its integration with MC practices in all decision categories and one of the highest interdependencies with other C4.0 technologies in the Jaccard index. This was expected because of the relative maturity of BIM-related research, which is associated with a wide variety of concepts that connects both C4.0 technologies (AR/VR, big data, modular and offsite construction, simulations models and tools, digital twins, among others) and MC practices. According to Maskuriy et al. [12], the application of most technologies in the construction industry could not be realised without BIM digital data as a collaboration medium. BIM can be regarded as a modelling approach that can support the management and decision-making regarding most of the MC practices selected by this study, such as managing the production of customised products, adopting information technology tools to support customers' choices, using prototypes to test and communicate solutions to stakeholders, and defining solution space through data analysis.

The findings also revealed additive manufacturing as an important technology regarding C4.0 and an MC strategy. It can be used for product prototyping and also for offering innovative customisation units, such as those related to sustainability and automation. It allows customisation units to be produced in short lead times while keeping inventories small.

Despite the potential for a positive impact of technologies such as human–computer interaction, radio-frequency identification and sensors, and predictive maintenance, they seemed to play a minor role in implementing MC strategies. The low indexes may also be associated with little awareness and poor understanding of those technologies in the construction industry [16].

Regarding the proposed method, it emerged as a simplification of the research method in order to assess the synergies and similarities of use of relevant items for a well-defined context. The results presented in this article can be considered as potentially useful to help decision-making in companies involved in the implementation of MC in the construction industry, as it makes a clear presentation of the synergies between MC practices and C4.0 technologies and the similarity of use and co-dependency between technologies. The qualities of these results are, of course, directly associated with the specialists' assessment, their previous experiences, and the context that was considered. However, it may extend the knowledge about the relationship between the MC and C4.0 as the list of items can be continuously updated and refined, considering the dynamic of innovation. Therefore, new decision categories and areas may emerge from those contributions. A key challenge is to find specialists with practical or academic experience in MC practices and C4.0 technologies, considering that these have not been widely implemented in the housing sector and the literature on C4.0 is recent.

Regarding the applicability of the method, its implementation was considered relatively simple as it involves a small number of specialists, a workshop, and the application of three equations. Moreover, the design of the method allows the choice of MC practices and C4.0 technologies that are applicable to a specific context, considering the perspective of the specialists involved.

Finally, the findings discussed throughout this investigation pointed out the interdependence and the need for joint implementation of different technologies [7]. This study reinforced the importance of discussing the practices and technologies as co-dependents, as they share similar and complementary features.

## 6. Conclusions

The main outcome of this investigation is the assessment of the synergistic potential between MC practices and C4.0 technologies and the similarity of use and co-dependency between technologies. The practices with the highest global synergy metrics include using specialised information systems to manage the production of customised products, adopting tools to support customers' choice, using prototypes to test solutions, and identifying customisable items that have high impacts on value generation. "Modular Construction", "BIM", and "Prefabrication/Offsite construction" stood out with the highest synergies with all MC practices selected by this study and with the highest indexes of similarity of use between technologies.

The findings and discussions enabled a better understanding of the potential synergies between both concepts, which were poorly explored in the literature from a broader perspective. Hence, results can provide a better understanding of MC and C4.0 by simply demonstrating the similarity of use and complementarity of the technologies and practices in a specific context in the construction industry.

The proposed method enables companies to select a set of practices and technologies relevant to their specific contexts. The simplification of some aspects of the research method can allow the proposed method to be widely implemented by companies in a relatively simple means through accessible tools and software. The selection of specialists is crucial as the results are based on their assessment. The discussions between specialists enable them to reach a consensual score or to identify knowledge gaps regarding some items or interactions.

A major limitation of this research work is that the proposed method emerged at the end of the investigation, and only an internal assessment by the research team was undertaken. The results presented in this investigation are based only on a small number of specialists who had in mind the specific context of the Brazilian housing sector, which means that the results cannot be generalised. It is necessary to apply the proposed method with other groups of specialists, considering other contexts, so that the knowledge about the synergies between C4.0 technologies and MC practices can be extended. Another limitation of this investigation is that the literature on C4.0 technologies is recent and ramping up.

Based on this study, some recommendations for future work have been made: (i) develop empirical studies in construction companies to understand how the synergies between MC and technologies have been explored in real-life applications; (ii) update or extend the set of MC practices in future replications of the proposed method, due to the intrinsic dynamics of innovation; (iii) assess the utility and applicability of the proposed method in other contexts; and (iv) connect MC and I4.0 from the perspective of Industry 5.0 as it shifts the focus from a technology-driven revolution to a value-driven initiative that drives technological transformation with specific purposes [97].

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