Demystifying the concept of offsite manufacturing method: Towards a robust definition and classification system

Kudirat Olabisi Ayinla

School of Engineering and the Built Environment, Birmingham City University, Birmingham, UK and School of Architecture, Computing and Engineering, University of East London, London, UK

Franco Cheung

School of Engineering and the Built Environment, Birmingham City University, Birmingham, UK, and

Abdel-Rahman Tawil

School of Computing and Digital Technology, Birmingham City University, Birmingham, UK

Abstract

Purpose: Offsite manufacturing (OSM) is continuously getting recognised as a way to increase efficiency and boost productivity of the construction industry in many countries. However, the knowledge of OSM varies across different countries, construction practices and individual experts thus resulting into major misconceptions. The lack of consensus of what OSM is and what constitutes its methods creates a lot of misunderstanding across AEC industry professionals hence, inhibiting a global view and understanding for multicultural collaboration. Therefore, there is a need to revisit these issues with the aim of developing a deeper understanding of the concepts and to ascertain what is deemed inclusive or exclusive.

Approach: A state-of-the-art review and analysis of literature on OSM was conducted to observe trends in OSM definitions and classifications. The paper identifies gaps in existing methods and proposes a future direction.

Findings: Findings suggest that classifications are mostly aimed towards a particular purpose and existing classification system are not robust enough to cover all aspects. Therefore, there is need to extend these classification systems to be fit for various purposes.

Originality: This paper contributes to the body of literature on offsite concepts, definition and classification, and provides knowledge on the broader context on the fundamentals of OSM.

Keywords: Offsite manufacturing; prefabrication; definition; classification; literature review

1. Introduction

The construction industry has for a long time been associated with inefficiencies, which is argued to be mostly facilitated by the traditional procurement and method of construction (Barbosa et al., 2017). This together with the increasing expectations of clients and end users creates pressure and opportunities for the industry to improve. Many governments, particularly those from the developed countries have created various incentives to encourage cross-industry learning from other industries such as automotive, aerospace and manufacturing with focuses on developing more efficient alternative construction methods through accommodating automation and standardisation of processes (Hairstans and Smith, 2018; Pan and Sidwell, 2011). In the UK, for instance, the government commissioned reports such as Latham (1994) and Egan (1998) have previously identified the needs and barriers for technologically-driven innovations. Offsite manufacturing (OSM) is seen as the approach to improve the products from the industry (Cabinet Office, 2011; HM Government, 2013), and a requisite to changing the craft-based and labour-intensive nature of the construction industry (Gibb and Isack, 2003; Miles and Whitehouse, 2013).

However, despite the recent increasing propagation of OSM, its diffusion and acceptance is still quite low in both developed and developing countries (Goulding et al., 2015). So far, apparent observation gathered from various publications on OSM shows a significant amount of issues inhibiting its wider acceptance in the construction industry of various countries. To start with, there is a lack of consensus or coordinated effort with regards to agreeing what shall be included in its definition (Baghchesaraei et al., 2015; Yunus and Yang, 2012). The lack of consensus further compounds the issue of how to appraise various OSM methods and compare them with traditional construction method (Abdullah and Egbu, 2010; Arif and Egbu, 2010; Azam Haron et al., 2015; Blismas et al., 2006; Pan et al., 2008; Song et al., 2005; Yitmen, 2007; Yunus and Yang, 2012). Other issues reported involves the unavailability of documented sources of information about modularization (Aldridge et al., 2001; Murtaza et al., 1993; Pasquire et al., 2005).

Although there are a lot of publications on OSM, the knowledge is not well structured and described as being fragmented (Blismas and Wakefield, 2007; Jabar et al., 2013). Some previous studies have reviewed the concept of OSM and developed different classification systems. Most of these classification systems are either based on the type of finished product (Gibb, 2001; Gibb and Isack, 2003; Jaillon and Poon, 2009), the process of manufacture (Lawson et al., 2010), the geometrical configuration of the product (Badir et al., 2002; Thanoon et al., 2003), or even the location of production (Mostafa et al., 2016). Kamar et al., (2011) reviewed the concept of Industrialised Building Systems (IBS) with the aim to develop a common definition and classification. However, the study is limited in terms of analysis and synthesis for recognising the commonalities and differences in definitions. Also, the classification system developed is only based on OSM products and missing other aspects like process and people captured in other literature materials.

This study aims to further the work of these researchers by synthesizing existing knowledge on OSM in construction through systematically evaluating the concepts of OSM from reviewed publications, and developing a more inclusive working definition and a comprehensive formalised classification of offsite vocabularies to enable common basis of evaluation and improve communication. The review includes (i) an evaluation of the definitions of OSM evolved over time (ii) an analysis of OSM taxonomies according to literature and other UK classification systems, (iii) development of a working definition and classification system for various purposes.

2. Methodology: Literature review analysis

A systematic analysis of exiting literature on OSM published since the 90s was carried out to identify its development and application in the construction industry. The review was conducted through four stages as illustrated in Figure 1: planning, screening and extraction, analysis and discussion, and documentation.

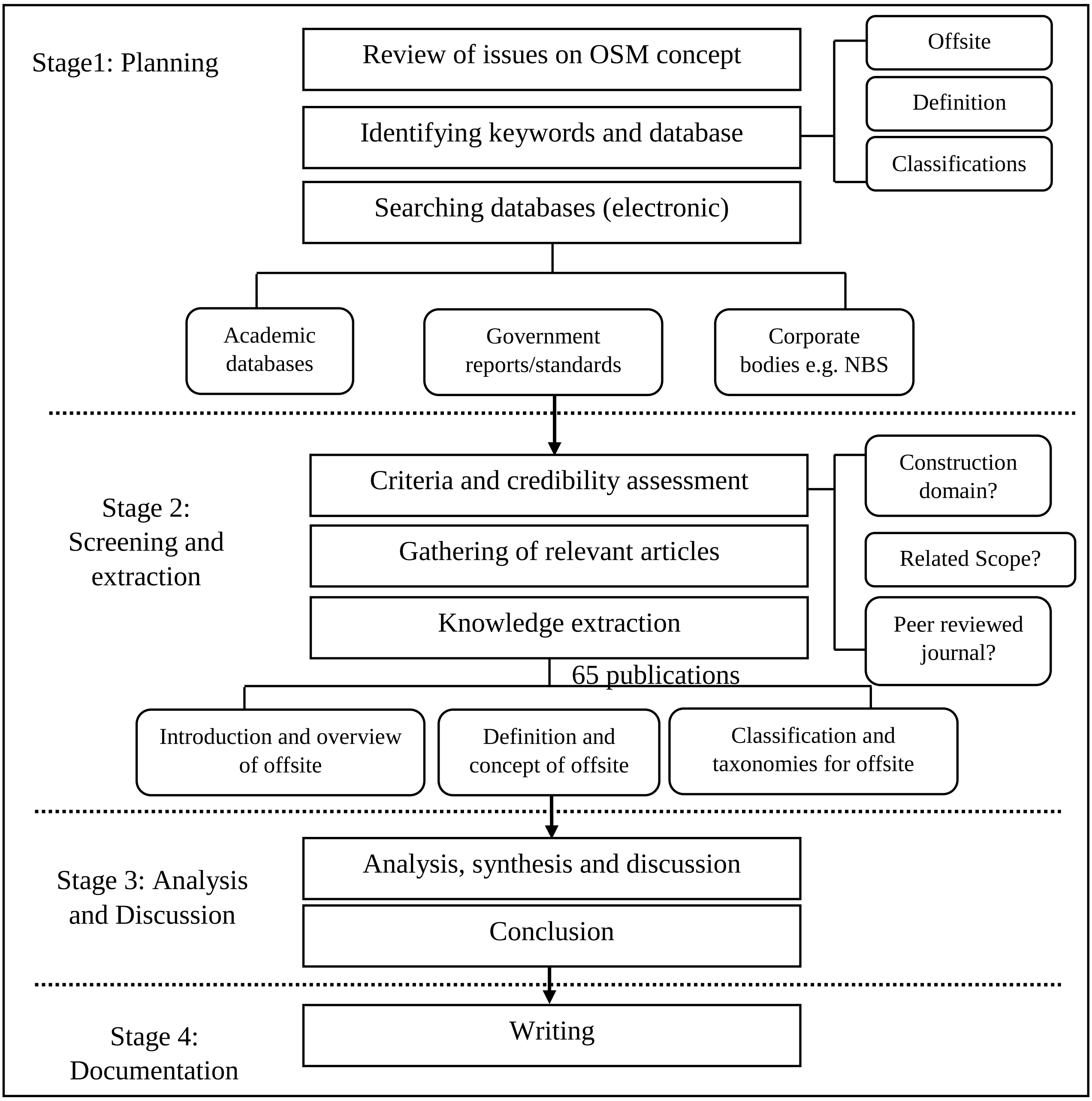


Figure 1: Research methodology and process flow chart

Stage 1: Planning

A search strategy was adopted to gather relevant publications on the subject area. Firstly, a set of relevant keyword phrases were identified for the search using the electronic database - ScienceDirect; some of which include 'offsite construction', 'prefabrication in construction', 'offsite manufacturing', 'offsite fabrication', 'industrialised building systems', 'system buildings', 'modern methods of construction', 'modular construction', building classification system etc. Use of keyword phrases is considered more application due to the need of ensuring that an exhaustive coverage by means of including as much work relevant for developing a comprehensive list of different definitions and classifications of OSM is achieved.

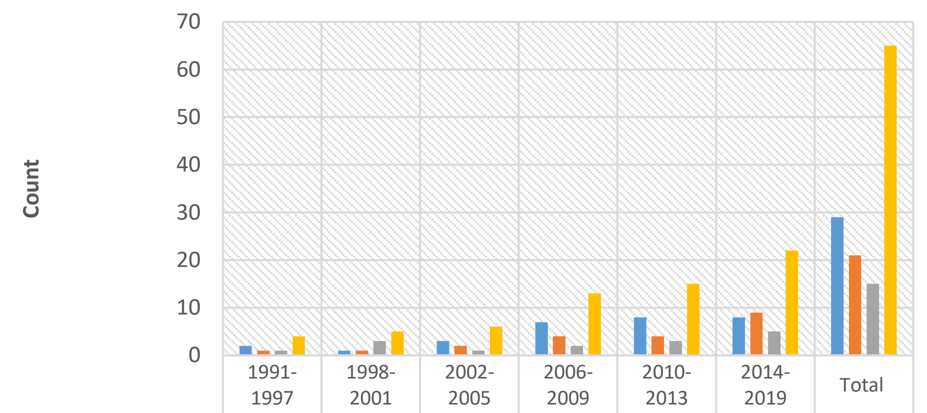
Supplementary searches were also carried out using other popular academic databases including Google Scholar, ASCE Library, Wiley, IEEE and Scopus. To include literature of OSM regarding its applications in practice, relevant government publications, industry standards and guidelines for OSM were also reviewed, e.g. published articles by corporate bodies such as BuildOffsite, National Building Specification (NBS), buildingSMART, Construction Industry Council (CIC), International Council for Research and Innovation in Building and Construction (CIB) and OffsiteHub) on offsite research and classification systems. The search resulted into a huge number of articles being retrieved.

Stage 2: Screening and extraction

The initial keyword search generated thousands of articles. To narrow the number of articles down, publications that are not construction related were eliminated. Further screening exercise was conducted where each article was skimmed through (for instance their abstract and conclusion) to examine their suitability to the analysis of the individual subjects. Articles with focus on peripheral subjects of OSM were considered out of scope and therefore excluded in the review. Remaining articles were then further screened out based on the criteria of (i) the credibility of such publications i.e. whether they are published in a peer reviewed journal or at least examined through a peer-review process, or widely recognised for industrial reports and textbooks and (ii) the type and source of such article. Overall, 65 journal papers/conference papers/books/reports were found suitable (Figure 2) and reviewed ranging from the 90s (although there was no restriction based on the year of publication during the screening exercise). . Reviewed publications were subsequently organised into themes according to the objectives of this study (Figure 3).

Stage 3: Analysis and synthesis of information

The selected papers were analysed and synthesised according to their similarities and differences in order to develop an insight on the topic and also identify gaps in current knowledge. This led to a high-level classification based on product, process and people which is followed up by an explanation of how they can be applied.



	1991-1997	1998-2001	2002-2005	2006-2009	2010-2013	2014-2019	Total
Journal Papers	2	1	3	7	8	8	29
Conference papers	1	1	2	4	4	9	21
Others	1	3	1	2	3	5	15
Total	4	5	6	13	15	22	65

Figure 2: Frequency and distinction of reviewed publications over a period of 28 years

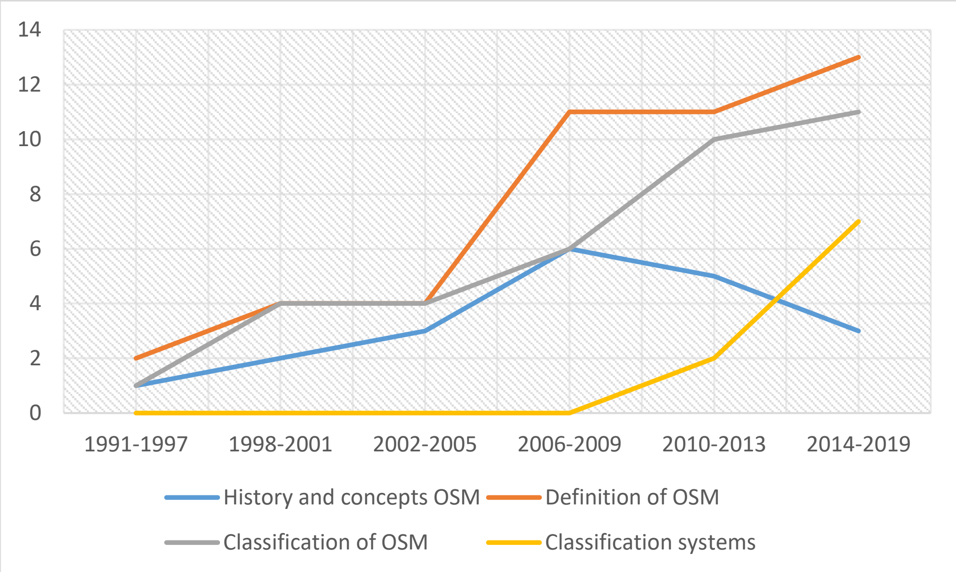


Figure 3: Number of reviewed publications yearly on different themes in the offsite domain

3. Defining offsite manufacturing (OSM) method

Definitions of OSM from 18 references are reviewed. Table 1 extracts and groups the definitions according to 4 categories - (i) *Pre* (as in *pre*fab, *pre*fabrication and *pre*assembly), (ii) *Building* (as in industrialised *building* system and system building), (iii) *Offsite* (as in *offsite* construction and *offsite* manufacturing), and (iv) *Modern methods* (as in *modern method* of construction and *modern method* of house building - defined by Pan et al. (2012) and highlights the common aspects of the definitions.

Table 1: Definitions of terms

Category	Term	Some key definitions	Source
'Pre'	Preassembly	"a ***process*** of ***manufacturing and assembly*** of building ***components*** in a ***factory environment*** prior to ***transportation*** … for installation."	(Gibb and Isack, 2003)
	Prefabrication	"describe the ***manufacturing process*** of ***components*** in a ***controlled environment*** … are ***assembled*** together to form components parts for ***installation***"	(Jaillon and Poon, 2009)
		"a ***manufacturing process*** and ***transporting*** to a site … to be ***erected or assembled***."	(Baghchesaraei et al., 2015)
		"… ***process of building components or full modules*** in … a ***factory environment***…."	(Richard, 2005)
		"… **a *manufacturing process***, generally taking place at a ***specialized facility*** and involves joining different materials to form a ***component*** part of the final ***installation***"	(Jaillon and Poon, 2008)
		"The ***manufacture*** of housing ***components*** offsite in a ***factory setting***"	(Steinhardt et al., 2014)
		"… a ***manufacturing and preassembly process*** in which joining of materials to forma ***component*** part takes place at a ***specified facility***"	(Chiang et al., 2006)
'Building'	Industrialised building system (IBS)	"… a construction process that involves the use of ***standardised mass produced building components*** in a ***factory or on site, transported and assembled*** into a structure using appropriate machinery"	(Musa et al., 2015)
		"… it requires the integration of smaller ***components and subsystems*** into an overall process/product with a full utilisation of ***industrialised production, transportation and assembly techniques***"	(Roy et al., 2007)
	System building (SB)	"…adopts the concept of ***mass production*** of ***building components* in a *controlled environment*** either onsite or offsite"	(Kamar *et al.*, 2011)
	Industrialised house building (IHB)	"… is used for describing a strategically different ***process- and product-oriented*** alternative to traditional project-oriented house-building methods and principles"	(Lessing et al., 2015)
'Offsite'	Offsite industrialisation (OI)	"… a process of moving construction operations traditionally undertaken on site to a ***manufacturing environment*** prior to ***final installation*** in required position"	(Zhai et al., 2014)
	Offsite construction (OSC)	"… the creation of built environment in a ***factory environment*** such that part of the construction ***process*** …	(Mtech Group, 2007)
	Offsite manufacturing (OSM)	"…a ***process*** that requires a higher percentage of the ***value-adding*** activities being carried out offsite (in a ***controlled environment***) with just ***installation and finishing*** done onsite."	(Jonsson and Rudberg, 2014)
		"… a unique mix of general construction procedures integrated into a ***production flow line*** ..."	(Nasereddin et al., 2007)
	Offsite manufacturing (OSM), offsite construction (OSC) and offsite fabrication (OSF)	"collectively used to describe a method of production and delivery through ***factory manufacture and assembly***"	(Miles and Whitehouse, 2013)
'Modern methods'	Modern method of house building	"manufacture of homes in factories with potential benefits"	(Post, 2003)

	Modern method of construction (MMC)	"as a description of new products, techniques and technologies in construction"	(Miles and Whitehouse, 2013)
		"… industrialisation as the use of advanced technology (mechanical tools, computerised systems) in a continuous process to improve efficiency in terms of ***standardisation, modularisation and mass production***"	(Girmscheid and Scheublin, 2010)

Observing from Table 1, the definitions seem to focus on either the nature of the finished product or outcome that is obtained (Musa et al. 2015, Roy et al. 2007, Li et al. 2016), the process of carrying out the construction (Mohd Kamar *et al.*, 2011; Zhai et al. 2014; Lessing et al. 2015), or both (Baghchesaraei et al., 2015; Lessing et al., 2015; Miles and Whitehouse, 2013). The common concept found in a number of definitions from the *Pre* and *Offsite* groups is the adoption of a manufacturing process, in which part of the production as components are assembled in a controlled working environment. The *Building* group contain the same fundamental concept together with standardisation or mass production as an additional element in the definitions, which arguably is a main contribution of the "higher percentage of the value-adding activities" in Jonsson and Rudberg (2014). The *Modern methods* group appears not limited to methods that integrate a manufacturing process and thus are more inclusive as alternative methods to traditional construction. (Kolo et al., 2014; McKay, 2010; Tennant et al., 2012). For instance, some *Modern methods* techniques are used in conjunction with onsite work hence forming a hybrid systems construction without any manufacturing process involved (e.g. Arbizzani and Civiero, 2013), which cannot be classified to be under the *Offsite* or *Pre* group. Thus, the other three groups can be considered as a sub-set of *Modern methods* and hence the authors do not consider *Modern methods* to be interchangeable with the other three groups.

According to Table 1, it is established that OSM terminologies in the Pre, Building and Offsite categories can be used interchangeably. However, the term 'modern methods' is a broader terms, which using the definition for OSM will not be considered satisfactory. OSM used in this paper is thus described as:

> *'the creation of a value-adding built environment through a combination of conventional construction procedures and production processes (as in product manufacturing) in which components for construction are produced in a controlled environment, and are transported and installed in the final position onsite.'*

It is important to note that the controlled environment referred to in the above definition is not limited to activities outside of a construction site. In the situation where a site is big enough to accommodate a factory or yard for production purpose, the production process can actually be onsite as seen in Young et al., (2015). Nevertheless, the finished components are required to be transported and installed to the final positions disregarding whether the production process is onsite or offsite. Also, the definition follows that of Jonsson and Rudberg's (2014) in capturing "value-adding" as the main rationale for offsite manufacturing processes as contrast to the counterpart of conventional onsite processes. It is then implied that value can be added through the adoption of standardisation, mass production, mass customisation and lean methodology as concepts found and applied in manufacturing processes.

4. Taxonomy of offsite manufacturing

4.1 Review and analysis of classification systems – based on literature

One general acknowledged classification for OSM adopted by most researchers (Arif and Egbu, 2010; Gibb, 2001; Gibb and Isack, 2003; Jaillon and Poon, 2009; Quale et al., 2012) is the subdivision of offsite manufacturing based on product orientation i.e. generic types according to the geometric shape, assembly approach, extent of offsite operation, and state of completion of the product. This type of classification was first suggested by Gibb (1999) with four groups identified, namely: *whole building/modular, volumetric pre-assembly, non-volumetric pre-assembly and component manufacture & sub-assemblies* (Table 2). Although widely recognised and accepted, Gibb's classification seems incomplete as other researchers (e.g., Abosoad et al., 2009; Hashemi and Hadjri, 2014) have identified similar product-oriented classification that incorporates panellised and hybrid systems products, which deviates from Gibb's (1999) classification. Inconsistencies are noticed in the various classifications. For instance, pods is considered as an independent type from volumetric systems according to Hashemi and Hadjri (2014) and Steinhardt et al. (2014) but the type is well within Gibb's definition for the volumetric sub-category as pods are three-dimensional volumetric building parts (Gibb, 2001). Perhaps, the type 'modular' is most confusing as Steinhardt et al. (2014) use the term 'modular' to refer to a level of prefabrication in a 6-level progressing continuum of a prefabricated house, from materials for a house (Level 1) to a complete house (Level 6) while other studies such as Arif and Egbu (2010), Gibb (1999), Mtech Group (2007) and Quale et al. (2012) consider 'modular' as a type of whole building offsite method. Also, Doran and Giannakis (2011) use the term 'modular' instead of offsite construction and sub-divide it according to (i) pure modular, (ii) hybrid modular, and (iii) onsite modular depending on the level and type of onsite activities. Their classification distinguishes onsite or offsite works involved in using a modular method with more attention to the design and construction approaches than the type of products or state of completion of a building. Furthermore, the location of production is used by Bari et al, (2012) and Mostafa et al. (2016) in their classification.

Mtech Group (2007) classified offsite according to the market sub-sectors including (i) complete structures (i.e., for permanent or reloadable volumetric units), (ii) structural elements and systems (i.e., for foundation, substructure, superstructure, building envelope or building services), (iii) civil engineering (i.e. for pre-assembled civil engineering structures) and (iv) special (i.e. for special structures or project specific offsite construction). Recognising the lack of common definitions and the arbitrary nature in classifying offsite construction, the suggested sub-sectors clearly follows the lineage of product-oriented classification such as Gibb's (1999) with slightly different groupings.

Table 2: OSM taxonomy according to literature

Group	Classification	Definition	Examples	Source
Product orientation	a. Whole building/modular	…make up the actual structure and fabric of the building. They enclose usable spaces and may be fully finished or partly finished	Retail outlets, office blocks and motels, concrete multi-storey modular units.	(Arif and Egbu, 2010; Gibb, 1999; Quale et al., 2012)
	b. Volumetric pre-assembly	Three-dimensional building parts that enclose a usable space. Installed onsite within independent structural frames and do not independently form the building itself.	Toilet pods, plant room units, kitchen spaces, stair shaft and building service risers and lifts, shower rooms etc.	
	c. Non-volumetric pre-assembly	Two-dimensional building components that do not enclose a usable space. May include several other sub-assemblies that constitute part of a building.	Pipework assembly, wall panels, structural sections such as slabs, beams, columns etc.	
	d. Component manufacture & sub-assemblies	Factory manufactured items that are manufactured offsite and will no way be considered for onsite production.	Bricks, tiles, window, lighting, door furniture etc.	
	a. Volumetric systems	Three-dimensional volumetric building units		(Abosoad et al., 2009)
	b. Panellised systems,	Two-dimensional building components	e.g. Slabs	
	c. Hybrid systems	A mix of two or more sub-categories and usually a combination of the volumetric and panelised sub-categories		
	d. Sub-assemblies and component systems	Small factory manufactured items	Bricks, tiles, window, lighting, door furniture etc.	
	e. Modular	Whole house building	Retail shops, whole residential houses	
	a. Panel systems (open & closed)	Two-dimensional building components		(Hashemi and Hadjri, 2014), (Hashemi, 2015)
	b. Volumetric systems	Three-dimensional volumetric building units	Kitchen, bath	
	c. Pods			
	d. Hybrid systems (semi-volumetric)	A mix of volumetric and panel systems sub-categories	Brick/block	

	e. Sub-assemblies and components	Small factory manufactured items		
	a. Construction materials b. Components c. Panels d. Pods e. Modular f. Complete	Standard building materials for construction Low level pre-cut or assembled components Structural elements defining space Volumetric units added to existing structure Volumetric units, joined onsite to form house Whole houses including multiple rooms and fittings.	Timber or bricks Trusses, doors Walls Bathroom pods Part-house Whole house	(Steinhardt et al., 2014)
	a. Sub-assembly components b. Volumetric c. Panelised d. Modular e. Site-based f. Hybrid	Factory-produced items not counted as full systems Factory-produced 3D units that enclose usable space Factory-produced flat panel units assembled onsite to produce the 3D structure. Preassembled volumetric units that jointly form the whole building A combination of volumetric and the panellised units	Floor cassette, roof cassette Bathroom pods, plant rooms, lift shafts Hotel modules Tunnel form, aircrete	(Abanda et al., 2017)
	a. Frame system (pre-cast or steel) b. Panellised system c. Onsite fabrication d. Sub-assembly and components e. Block work system f. Hybrid System	Load bearing components 2D components A mix of two or more sub-categories	Precast concrete framing, prefabricated timber framing system and steel framing system Roof truss, balconies, staircases, toilets, lift chambers	(Kamar et al., 2011)

	g. Volumetric and modular system	3D modules systems		
Modular type	a. Pure modular b. Hybrid modular c. Onsite modular	Do not accommodate changes, design is predetermined thus renders the client fully obliged to accepting the available design options Combination of onsite and offsite methods which allows customisation and it is associated with a higher requirement for coordination Pre-manufacture of modules onsite thus accommodating greater flexibility in terms of transportation		(Doran and Giannakis, 2011)
Location of production	a. Offsite production b. Onsite production	Involves transferring building operations from site to factory Involve casting structural building elements at the site before erecting to its actual location		(Bari et al., 2012; Mostafa et al., 2016)
Market sub-sector	a. Complete structures (permanent or reloadable) b. Structural elements and systems c. Civil engineering d. Special		Relocatable volumetric units, Permanent volumetric units Foundation Substructure Superstructure Building envelope Building services Preassembled civil engineering structures Special structures	(Mtech Group, 2007)
Production process	a. Static production b. Linear production	Module is manufactured in one position, and materials, services, and personnel are brought to the module Manufacturing process is sequential, and is carried out in a discrete number		(Lawson et al., 2010)

	c. Semi-automated linear production	of individual stages that is analogous to automotive production lines Based on the same principles of conventional linear production as non-automated lines, but tend to have more dedicated stages.		
	a. Factory production b. Workshop production	Features moving assembly lines with different stations Small open-plan buildings where products are moved between material and workers and modules are assembled without being moved		(Duncheva and Bradley, 2016)
Geometry and configuration	a. Linear or skeleton b. Planar systems c. Box systems	Load bearing structures that transfer vertical and/or lateral load. Structures where load are distributed through large floor and wall panels Structures that do not support vertical loads itself	Beams and columns system, Panellised systems-slab, floors Three dimensional modules	(Warszawski, 1999)
	a. Frame systems b. Panel systems c. Box systems	Load bearing structures that transfer vertical and/or lateral load to the foundation. Refer to structures that carry load through slabs (i.e. floor) and wall panels Structures that do not support vertical loads itself but rather depends upon the panel systems to carry their load an also provide lateral stability.	Include beams and columns Slabs (i.e. floor) and wall panels Kitchen and bathroom pods	(Badir et al., 2002)
	a. Frame or post and beam system b. Panel system (2D structural elements) c. Box system (3D elements)	Structures that carry the loads through their beams and girders to columns and to the ground Structures where load are distributed through large floor and wall panels. Systems that employ three-dimensional modules for fabrication of habitable units, which are capable of withstand load from various directions due to their internal stability.		(Roy et al., 2007) (Thanoon et al., 2003)

	a. Frame b. Panel c. Cell	Load bearing components, 2D components ideal for façade application whether straight, curved or angled. 3D modules systems		Baghchesaraei et al. (2015)
Others	a. Frame system b. Panel system c. Onsite fabrication d. Sub-assembly and components e. Block work system f. Hybrid system g. Volumetric / Modular system			Musa *et al.*, (2015)

Another product aspect that has been used for classification is according to its geometry and configuration. For instance, researchers have come up with a classification for industrialised building systems (IBS) based on the geometry and configuration of framing components regardless of their enclosing materials. Warszawski (1999) gives IBS classification as (i) linear or skeleton (as in beams and columns) systems, (ii) planar systems (panellised systems) and (iii) three dimensional or box systems. Similar classifications are used by Badir et al. (2002) for precast concrete IBS and Roy et al. (2007) for housing. There is, however, a major doubt about this type of classifications in terms of its completeness and practicality. According to Thanoon *et al.*, (2003), some new innovative systems could not be classified under this categorisation, such example is the interlocking load bearing blocks, which does not fall into any of the three categories. Additionally, Lawson et al. (2010) classified OSM according to various production processes as: static production, linear production and semi-automated linear production depending on the design of the production line while Duncheva and Bradley (2016) termed the processes as: factory and workshop production. Both classifications are similar in definitions but Lawson et al.'s (2010) classification gives room for a combination of both with their semi-automated linear production category.

The review reveals different perspective on OSM classification and a lack of consensus with regards to how OSM is to be classified, and what is deemed inclusive and what is not. The lack of a generic and standard classification has led to confusion and discrepancy especially when a classification system is needed in order to perform specific task (e.g. cost estimation). For instance, according to Kamar et al. (2011), the block work system sub-category is being separated from components and sub-assemblies even though most definitions of sub-assembles insinuates that block work is an example of this category. Also, Baghchesaraei et al. (2015) in their recent study argue that prefabrication should be divided according to criteria such as materials, methods, and structural configuration. However, their classification can only be grouped under structural/geometrical configuration. Similarly, Musa *et al.*, (2015) argue that the classification of IBS should be based on three criteria – materials, process and systems. However their classification does not reflect enough the categories they proposed.

4.2 Review and analysis of classification systems – based on UK construction industry standards systems

Apart from the attempts by researchers in previous studies to classify OSM, some standards classification systems have also been developed in the UK construction sector for classifying OSM for different purposes, e.g. for design and building information modelling such as (i) Uniclass 2015 classification system and (ii) Industry Foundation Classes respectively. These classifications systems are reviewed and compared to the existing taxonomies in literature materials.

(1) **Uniclass 2015** is a classification system used to represent all construction sector in the UK. The classification system is aimed at providing a structured library of materials and product model and project information (Afsari and Eastman, 2016). It provides an information structure which is useful for categorising information for costing, briefing, preparation of specification documents and layering of CAD drawings (Delany, 2015).

Table 3: Uniclass 2015 classification for prefabricated frames and walls (Source: NBS 2015)

Group	Element/Code	Systems/Codes
20	Frames (EF20_10)	Prefabricated framed and panelled structures (Ss_20_10_60)
		Prefabricated room systems (Ss_20_10_65)
		Composite pods (Ss_20_10_65_15)
		Concrete pods (Ss_20_10_65_17)
25	Walls (EF_25_10)	Prefabricated metal wall systems (Ss_25_12_85_60)
		Prefabricated glass block wall systems (Ss_25_13_33_64)

For off-site products, the top level of classification under Uniclass 2015 is 'Entity', which is a discrete unit such as a building, bridge or tunnel (Delany, 2015). The information for these suite according to the Uniclass can be broken down further into Elements, Systems and Products according to the level of granularity. An element can be made up of a system or a collection of systems and a system is composed of individual products. For instance, the element 'wall' for a building can be composed of two systems, masonry wall systems and prefabricated metal wall systems. Masonry wall systems will typically include a collection of insulation, blockwork, brickwork, and wall finishes whereas prefabricated metal wall systems may include a collection of metal studs, metal joist, plasterboard, insulation and wall finishes.

The products for the prefabricated metal wall systems may include aluminium, hardwood, light steel frames (LSF) etc. In Uniclass 2015, prefabricated systems and product are not independently classified, rather they are listed together across each element group thus making it difficult to extract a holistic product list if a fully prefabricated building is involved. As a result, efforts was made to identify instances of prefabricated systems in the element groups *Frames* (group 20) and *Walls* (group 25) as an example for the review (Table 3).

Based on the classification, panelled offsite structure and room systems are classified under the group element frames, which do not follow the trend and definitions previously examined in the literature (section 4.1). Review of literature materials describes frame offsite systems as load bearing structures that transfers vertical loads (Badir et al., 2002; Kamar et al., 2011), which in their case can be prefabricated columns or beams. Thus, a prefabricated room or pod system (i.e. volumetric) does not qualify under the frames group element. Also, a wall being a two-dimensional system is normally classified as a panelised system of OSM whereas it is classified differently from panels in Uniclass 2015. If classifications are a means of grouping things with similar characteristics, then a prefabricated metal-framed wall system is more likely a branch of panellised elements. Also, there is no classification for whole house offsite systems, which is a typical product category different from a room unit volumetric system (Gibb, 1999) as reviewed earlier. To conclude, it is difficult to consistently evaluate OSM options with the use Uniclass 2015's classification.

(2) **Industry Foundation Classes (IFC)** was first developed to serve as a standard format for data exchange in the AEC industry. It is a high-level object-oriented data model for all types of AEC projects that gives a hierarchical structure of different aspects ranging from building, geometry properties, materials properties, organisations and many more (Froese, 2003). IFC classification is used to arrange the objects of common characteristics or purposes (buildingSMART, 2016). IFC classifies object models and allows different classification systems to be referenced (Grani, 2016) in a situation where there is need to adopt a specific classification system or where IFC does not include enough information of properties and attributes of an object (Grani, 2016). The latest standard is IFC4 Addendum 2, which was published in 2016 (buildingSMART, 2016). IFC classifies building element as *IfcElementType* when populating values for export (*IfcExportAs)* between different applications and systems. The group *ifcSharedBuildingElements* (Table 4) represents the high level categories of building elements used to represent the architectural design of a building according to IFC4.

IFC4 group element however does not include provisions for prefabricated systems such as volumetric units (e.g. pods, room units) and whole building systems, also prefabricated panel systems are not specifically categorised. This is perhaps because the data exchange format (i.e. IFC) has been mainly driven by the need of designers who are traditionally not trained to design with the use of OSM. Thus, the data structure in IFC emulates the traditional approach to element classification and attribute assertions. This is a major concern to use IFC as a basis for sharing information of prefabricated elements as it may result in a lot of inconsistency and incompleteness regarding the information created and shared.

Table 4: IFC4 Add2 building element classification (Source: buildingSMART 2016)

Group	Type
IFC Shared Building Elements	IfcBeamTypeEnum
	IfcBuildingElementProxyTypeEnum
	IfcBuildingSystemTypeEnum
	IfcChimneyTypeEnum
	IfcColumnTypeEnum
	IfcConnectionTypeEnum
	IfcCoveringTypeEnum
	IfcCurtainWallTypeEnum
	IfcDoorTypeEnum
	IfcDoorTypeOperationEnum
	IfcMemberTypeEnum
	IfcPlateTypeEnum
	IfcRailingTypeEnum
	IfcRampFlightTypeEnum
	IfcRampTypeEnum
	IfcRoofTypeEnum
	IfcShadingDeviceTypeEnum
	IfcSlabTypeEnum
	IfcStairFlightTypeEnum
	IfcStairTypeEnum
	IfcWallTypeEnum
	IfcWindowTypeEnum
	IfcWindowTypePartitioningEnum

5. Discussion

5.1 Classification system for OSM

The review from the previous sections reveals the differences in classifications of OSM. By synthesizing the data retrieved from previous studies for the purpose of comparing evidence to generate new construct, it is established that various factors influences how OSM is classified, this includes: materials type, production methods, products types and sizes, and structural configuration. These various factors can however be grouped under three high-level concepts which are (i) based on product (ii) based on process (iii) based on people (Figure 4). This classification system in Figure 4 summarises the different approaches previously reviewed and should help achieve consistency in terms of the use of agreed vocabularies and also enhance communication. The use of OSM related keywords in the definitions and classifications is due to the rationale behind the development of structured knowledge. The aim is to use a set of approved vocabularies by the experts in the field in order to aid communication.

One major advantage of classifying in this approach is the ability to make the classification robust enough and suitable for different purposes. For instance, the knowledge of OSM may be needed for various purposes such as costing, risk management, scheduling, production sequence planning and many other tasks. A further explanation of these are outlined in sections 5.1.1, 5.1.2 and 5.1.3.

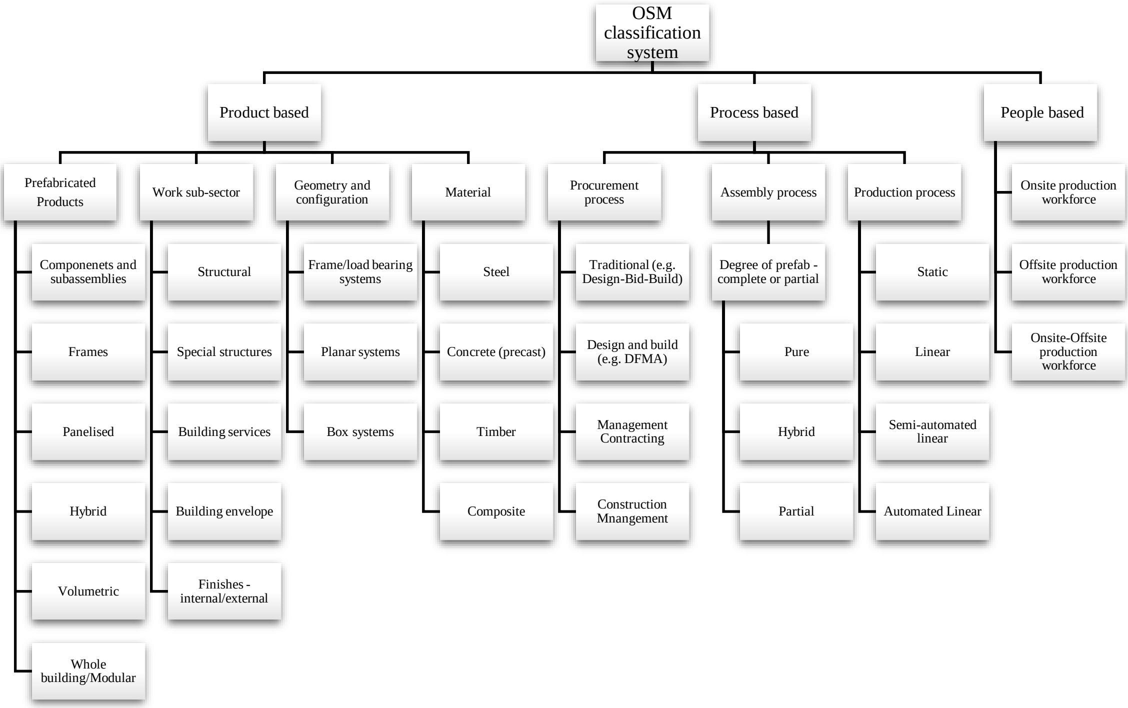


Figure 4: OSM Classification

5.1.1 Product-based classification

The product-based classification for OSM is according to the characteristics and types of the end/finished product of an offsite manufacturing process, which include: the types of prefabricated elements, component materials, geometry and sector of work for a product (Table 5). This classification is useful for identifying types of offsite manufactured products and grouping them for specific purposes. For instance, the product-based classification will be useful for elemental costing purposes to attribute properties to each offsite elements or components. As an example, a prefabricated product typically has a material type, geometry and also fall under a specific work sub-sector (e.g. a panelised offsite product made from timber has a plane geometry, and can either be grouped as a structural element – e.g. load-bearing wall, or building envelope – e.g. curtain walls). Accordingly, the knowledge of offsite products is enriched through defining the relationships between the various properties and the influence on the final cost of such element.

Table 5: Definition of concepts in the product-based classification

Class	Subclass	Instances	Description
Prefabricated Products	Components and sub-assemblies	Bricks, tiles, window, lighting, door furniture etc.	Factory manufactured items that are produced offsite and certainly not considered for onsite production.
	Frames	Beams, columns, bracings etc.	Load bearing structures that transfer vertical and/or lateral load to the foundation.
	Panelised	Wall panels, floors panels etc.	Two-dimensional building components that do not enclose a usable space and may include several other sub-assemblies that constitute part of a building.

	Hybrid	Roofs	A mix of two or more sub-categories and usually a combination of the volumetric and panelised sub-categories.
	Volumetric	Toilet pods, plant room units, kitchen spaces, stair shaft and building service risers and lifts, shower rooms etc.	Three-dimensional building parts that enclose a usable space but do not independently form a building itself.
	Whole building	Retail outlets (shops and stores), office blocks and motels	They enclose usable spaces and make up the actual structure and fabric of the building. Usually a low rise complete building which may be fully finished or partly finished
Work sub-sector	Structural	Columns, beams, foundations, walls etc.	Primary physical parts of a building
	Building services	Pods, Lifts, plant room etc.	Systems installed in buildings to enhance functionality
	Building envelope	Façade systems, roof systems	The exterior of a building which serves as physical separator between the interior and exterior of a building
	Finishes	Plaster, paints etc.	The final surface of a building element
	Special structures	Unique structures e.g. stadia	Structures that require engineering creativity and specialist design, analysis and construction
Geometry and configuration	Frame system	Beams and columns	Load-bearing structures
	Planar system	Slab, floors, wall panels etc.	Two-dimensional components that may be straight, curved or angled
	Box system	Kitchen and bathroom pods etc.	Three-dimensional modules that do not support vertical loads itself.
Materials	Steel	Lightweight steel etc.	A metal part containing iron as a primary material
	Concrete (precast)	Self-compacting concrete, lightweight concrete etc.	Comprising of a mixture of cement, aggregate and water where components are manufactured in a central plant and later brought to the building site for assembly.
	Timber	Bamboo, Oak, plywood, soft wood etc.	Wood suitable for engineering purposes.
	Composite	Fibre-reinforced polymer (FRP), PVC polyester etc.	Comprising two or more constituent materials with significantly different physical or chemical properties

5.1.2 Process-based classification

OSM can also be classified based on its processes including the procurement process (i.e. the sequence of design to production and whether the design approach attempts to integrate the ease of manufacture and efficiency of assembly or to address conventional construction design concerns), the assembly process (i.e. the extent in which manufactured components are complete for assembly) or production process (i.e. the methods employed in producing the manufactured components such as the use of innovative technologies and amount of skilled/unskilled labour required) (Table 6). For instance, an OSM project can be procured via a traditional design-bid-build approach where the subcontractor or specialist contractor undertakes production in a way similar to the onsite approach (i.e. static production method). Alternatively, a production can be carried out sequentially on a line with the use of robotics stationed at strategic points to hasten the process (i.e. an automated linear production). In a situation where the advantages of modularisation is more desirable, all components can be factory manufactured with only assembly done onsite (i.e. pure prefab). Describing OSM in this manner is advantageous for purposes such as planning and scheduling of the production and assembly processes.

Table 6: Definition of terms in the process-based classification

Class	Instances	Description
Procurement process	Traditional – design-bid-build	Where the client appoints consultants to design the development and then a contractor to construct the works, the contractor has little or no influence on the design.
	Design and build - DFMA	A single contractor to design and build the work and the contractor has a say in the design process. The contactors has little or no influence on the design.
	Management Contracting	A management contractor contracts and manages the work to other work contractors to construct the work.
	Construction Management	A construction manager to serve as a representative of the client in coordinating all work contracts and other trade contractors
Production process	Static	A process where prefabricated elements are manufactured in one position, and materials, services, and personnel are brought to the fabrication point.
	Linear	Production process is sequential and carried out in a discrete number of individual stages.
	Semi-automated linear	Based on the same principles of conventional linear production as non-automated lines, but tend to have more dedicated stages
	Automated linear	Linear production with sequential stages that are automated
Assembly process	Pure prefab	All activities carried out in a controlled environment (either offsite or onsite) with only assembly and installation done onsite.
	Hybrid prefab	Comprising of both onsite and offsite prefabricated components assembled together. For instance, an onsite factory produced element joined together with an offsite purchased structural element to make a complete structure.
	Partial prefab	A mix of offsite factory produced components and onsite cast insitu components.

5.1.3 People-based classification

This category gives information on the degree of prefabrication and category of workforce required for an offsite product manufacture i.e. whether products are manufactured/assembled using onsite or offsite labour, or a combination of both (Table 7). The choice of production/assembly process influences the type/characteristics of workforce required. If a higher degree of prefabrication is sought, the amount of work that needs to be finished off in the factory will be higher and thus, required more onsite activities and workforce, and a few workforce onsite for just assembly. This classification system may be used in carrying out tasks such as risk assessment or health and safety analysis both onsite and offsite, as well as generating onsite/offsite labour cost for offsite manufactured products.

Table 7: Definition of terms in the people-based classification

Class	Instances	Description
Organisation	Offsite	Involves transferring building operations from site to factory using factory located personnel.
	Onsite	Involves the production of building elements at the site before erecting to its actual location using site based personnel.
	Onsite-offsite	Involves a mix of both offsite and onsite production and assembly team.

6. Conclusion and future work

6.1 Conclusion

Offsite manufacturing (OSM) as a domain is reviewed to identify issues with its definitions and classification systems. Finding from the review suggest that there is a great level of misconceptions about its definition and taxonomies. This paper proposes a definition and classification approach which combines the essential elements of existing classifications. The following conclusion has been drawn from the review:

- Although OSM is defined differently by most researchers in the field, most existing definitions covers mostly the essential aspect that distinguishes OSM concept from the conventional approach. However, elements of the benefits of modularisation and standardisation are largely missing from most of the definitions.
- There is a significant lack of consensus on OSM classification approach thus leading to misunderstanding on what should be regarded as part of OSM and what is not. Researchers tend to classify OSM based on the particular theme of their study or the purpose for which the classification is needed.
- Existing classification system in the UK such as Uniclass and IFC are limited in terms of providing a detailed level classification for OSM compared to traditional approach. These classification systems needs to be consistent in describing major OSM classes and their sub-classes, and also should be extended to cover missing elements and serve as a basis for a unified approach for classifying OSM.

Although attempt has been made in this study to develop a generic definition and classification system for OSM. This is only based on high-level concepts and essentially to identify common traits and include all aspects from previous classification systems. The generic classification for OSM will need to be extended in order to provide a more robust system fit for different purposes. The authors believe that to fully benefit from the classification system, there is a need to adopt both top-down and bottom-up approaches. The attempt to review previous works on classifications in this study to develop the high-level OSM classification is an example of a top-down approach to integrate the existing ideas and concepts. Efforts will need to be spent on developing the classification further using a bottom-up approach as well, i.e. through capturing knowledge from individual cases of offsite (e.g. steel, timber or concrete offsite systems), as OSM knowledge is likely highly specialised and can involve a lot of localised properties that is not necessarily possible to be generalised without learning from actual cases.

6.2 Future work

This research has highlighted areas of opportunities with regards to OSM classification. Based on the classification system developed, there are several areas of research arising from the study which will need to be pursued. There is need to consider the application of more scientific approaches recognised for knowledge development in a specific domain. An example is the use of ontology knowledge modelling approach for the formalisation of offsite vocabularies to enable knowledge extraction and facilitate communication. This would benefit from the bottom-up approach through the use of case studies to determine finite level classes, subclasses and properties and their corresponding relationships so as to facilitate automated retrieval on information for various purposes (e.g. cost estimation). The formalisation of offsite knowledge through an ontology development gives transparency and the ease of communication for professionals, and the potential to automate advices using software applications.

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