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Open manufacturing: a design-for-resilience approach

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ABSTRACT
Open systems have been of interest to the research and industrial community for decades, e.g. software development, telecommunication, and innovation. The presence of open manufacturing enterprises in a cloud calls for broadly interpretable models. Though there is no global standard for representation of digital models of processes and systems in a cloud, the existing process modelling methodologies and languages are of interest to the manufacturing cloud. The models residing in the cloud need to be configured and reconfigured to meet different objectives, including complexity reduction and interpretability which coincide with the resilience requirements. Digitisation, greater openness, and growing service orientation of manufacturing offer opportunities to address resilience at the design rather than the operations stage. An algorithm is presented for complexity reduction of digital models. The complexity reduction algorithm decomposes complex structures and enhances interpretability and visibility of their components. The same algorithm and its variants could serve other known concepts supporting resilience such as modularity of products and processes as well as delayed product differentiation. The ideas introduced in the paper and the complexity reduction algorithm of digital models are illustrated with examples. Properties of the graph and matrix representations produced by the algorithm are discussed.

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Open manufacturing; design for resilience; complexity reduction; decomposition; cloud manufacturing; service manufacturing

1. Introduction

Traditional manufacturing has been centralised and protective about its processes and physical assets. This has been especially applicable to enterprises with products dominating the market. Once businesses begun exploring production across global locations, manufacturing has naturally become distributed. This global manufacturing expansion has been largely driven by lower production costs. The design and manufacturing of products offered at the domestic markets has been also impacted by some research, development, and design activities performed globally.

The new manufacturing world order is making some of the traditional production models more open. This paper focuses on the open manufacturing extreme, rather than the integrated manufacturing extreme discussed in (Kusiak 2020). The factors impacting this profound manufacturing openness, i.e. digitisation, service orientation, and cloud solutions, are discussed.

Open systems and architectures have been subject to intense research and industrial activity, e.g. software industry, telecommunication, and innovation. There is no uniform definition of an open system, rather different application domains provide their own definitions. The use of the term open ranges from context such as open economy to open software and open innovation.

The definition of open manufacturing used here follows that of open system architecture, widely used in the telecommunication and computing systems. These systems are globally distributed, use different equipment and software, and process information across the globe.

The open system architecture in telecommunication has the following characteristics:

- Allows to perform system description, design, development, installation, operations, and maintenance at any layer of the hierarchical architecture,
- The functions of a lower layer are used and controlled by the higher layer,
- Each layer can be implemented without interfering with the other layers,
- Change of performance in one or more layers does not impact the hardware, procedures, and protocols in remaining layers.

The open system architecture has been formalised as the OSI (Open System Interconnectivity) model. The OSI

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model has been approved by the ISO (International Standard Organization) in 1984 after years of international collaborative efforts. The definition of the OSI model makes it a likely candidate model for open manufacturing.

The open system architecture has been embraced by the U.S. defense industry to design and organise complex systems due to its emphasis on modularity, standardisation, and use of common interfaces to increase system interoperability. The open model requires business transparency that leverages the collaborative potential of participants, shares risk, maximises asset reuse, and reduces the total ownership costs. The Better Buying Power 3.0 directive of the U.S. Department of Defense adds significance to the open system architecture.

The research discussed in this paper is to mitigate negative impacts of any large-scale political, natural, social, or pandemic event. While the industry undergoes digital transformation, an opportunity has emerged to make manufacturing resilient. This is because the former implies process changes that may include resilience as one of the objectives. The transformation of industry will naturally result in changes visible on different scales, e.g. from deployment of new equipment and software in a short term to a different mix of skills due to new technologies over a longer time horizon. It is important that factors impacting manufacturing in long term are considered. One may argue that since the industry is entangled in a digital transformation, changes of different magnitude may be bundled to reduce the implementation cost and increase their impact. Casting a wide net of requirements related to different objectives, including long-term ones, while planning a change is worthy consideration.

The long-term objective that needs attention is resilience of manufacturing industry, which could be incorporated in the digitisation initiatives. Manufacturing resilience has different facets and it naturally supports the requirements of the production of the future. Here, manufacturing resilience is defined as the ability of a business to adapt and function at a desired level in the presence of adversities ranging from natural disasters to pandemics.

The list of factors potentially impacting resilience include energy, materials and components, processes and physical assets, transport, supply chains, reconfigurability, logistics, productivity, capacity, quality, sustainability, workforce, social factors, natural disasters, cybersecurity, and pandemics (Kusiak 2019). Though some of these factors may seem distant from the manufacturing and service resilience equation, closer analysis may prove a valid relationship. Each resilience factor can be expressed in different forms, metrics, and variables. The form of expression depends on the nature of the factor, availably of data, and the application needs. Research is needed to define these measurements and the data origin. The dependency among all underlying variables should be considered.

Global issues such as climate change, pollution, and travel have generated interest in resilience of infrastructure, transportation, energy, and water. Manufacturing and service industry as the base of economic activity deserve a comprehensive approach to understanding and modelling resilience to benefit the society and economy. It is not enough to think that shortage of materials and components attributed to the politics, natural disasters (e.g. earthquakes), or pandemics are the only factors impacting resilience, rather a detailed analysis of all existing and emerging inputs to the manufacturing and service industry is needed. Mitigation strategies to address manufacturing resilience are overdue.

Manufacturing resilience could be handled at a design or an operations phase. Most literature has focused at the latter phase, which limits the opportunities to improve resilience by the design decisions made.

This paper addresses resilience at the product and manufacturing design phase. The domains of products and manufacturing are accustomed to design-for-X rules, e.g. design for reliability. Here, an extension of the design-for-X towards resilience is proposed. The concepts of open manufacturing, complexity reduction of models, modularity, and delayed product differentiation are suggested as the design-for-resilience principles.

2. Literature review

The term open system in a manufacturing context dates years ago, e.g. Lin and Solberg (1994) introduced agents in an open system for autonomous production scheduling and control.

The concept of social manufacturing and open design were introduced in Lanz and Järvenpää (2020). The authors advocated the power of communities in the design and manufacture of products. They have acknowledged the existence of various forms of social manufacturing, e.g. personalised products. Kim et al. (2010) offered a glimpse of openness by applying the manufacturing message specification (MMS) protocol to the integration of MMS-compatible and non-MMS-compatible manufacturing equipment. Following the previously developed architectures (e.g. Camarinha-Matos, Afsarmanesh, and Osorio (2001), Sandakly et al. (2001)), Giret, Garcia, and Botti (2016), proposed an open architecture utilising agents that was amenable to e-manufacturing systems. Ghomi, Rahmani, and Qader (2019) reviewed concepts, architectures, and platforms of cloud manufacturing.

Though similar in name, the development of open source software (OSS) does not have much in common with open manufacturing, yet some concepts could be shared across the two domains. Open source software projects (e.g. Apache, Linux, MySQL, R, Perl, and Open Office) have been developed by volunteers (Fang and Neufeld 2009). The very fact that they embody views of a large community, make them attractive and widely used. This has been confirmed by Dong, Wu, and Zhang (2019) in the analysis of relationship between the release speed of open source software and the number of downloads.

Open innovation has been studied with a growing intensity as it provides opportunities ranging from market success to reduced product development time and cost. Though the open innovation comes at a cost, Munir, Runeson, and Wnuk (2018) have demonstrated that a well-managed openness, increases business competitiveness. The goal of open innovation is to connect and find the best solution to the innovation problem (Sigalovsky et al. 2015). Such a solution may reside outside of corporate research organisations. The authors have discussed the functional TRIZ (Theory of Inventive Problem Solving) approach to increase effectiveness of open innovation. Masucci, Brusoni, and Cennamo (2020) investigated open innovation strategies aimed at accelerating innovation. The analysis of five innovative projects has led to determining factors critical to the successful deployment of technologies, a potential to broaden a portfolio of service providers and retention control of intellectual property. Inbound open innovation is an innovation practice where a corporation utilises external knowledge and technology to its innovation. Lyu et al. (2019) researched the impact of network embeddedness on inbound open innovation in the presence of technology clusters. Sivam et al. (2019) analysed factors enhancing open innovation. Examining conditions under which external knowledge would benefit a corporation was the focus.

The bibliometric analysis of the resilience related papers in the Scopus database in the period of 2015–2020 has produced the map shown in Figure 1. The search conducted of two keywords ('resilient design', 'resilient operation') did not produce a meaningful return on the published design-for-resilience research. The previously published papers on resilience have been largely grouped around the 'operation' and 'analysis' attributes that are clearly visible in Figure 1.

Each of the two attributes is associated with attributes occurring at lower frequencies, however, none of them points to the design-for-resilience approach discussed in this paper. Examples of previously published papers on resilience in manufacturing include the review article

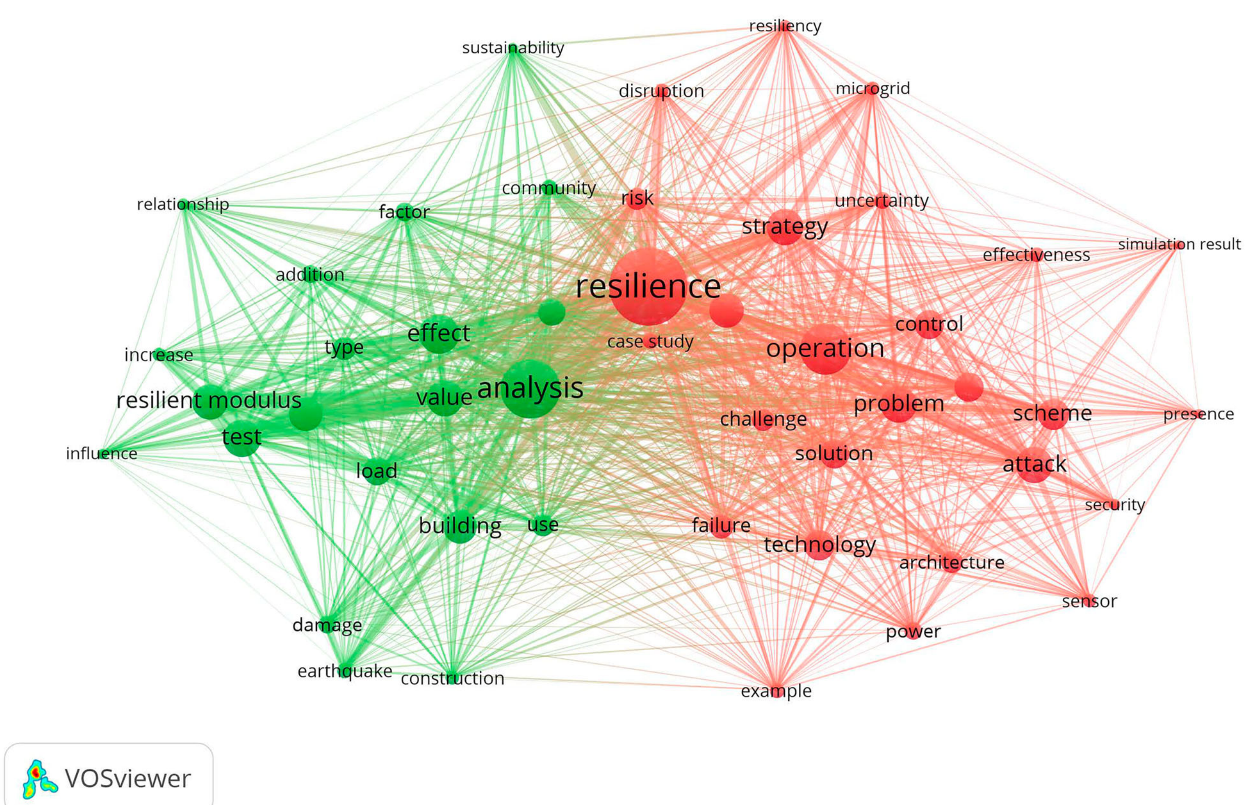

Figure 1. Bibliometric analysis of 1445 resilience related journal papers.

by Bhamra, Dani, and Burnard (2011), which is one of the special issue papers. The authors reviewed the resilience literature at an organisational level. Areas for future research such as study of the relationship between human and organisational resilience and understanding interfaces between organisational and infrastructural resilience were highlighted. The organisational resilience and buyer–supplier–supplier relations were presented by Borekci, Rofcanin, and Gürbüz (2015). Ivanov and Dolgui (2019) discussed resilience of supply chains with the focus on digital technology. The concept of low-certainty-need was introduced to enhance resilience of supply chains. Panetto et al. (2019) emphasised complexity and heterogeneity of the enterprises of the future along with supply chains, decision-making, and sustainability. The literature on resilience in manufacturing on a broad set of attributes ranging from material and processes to sustainability was reviewed in Kusiak (2019).

3. Drivers of open manufacturing

The main drivers of manufacturing openness are digitisation, service orientation, and presence in a cloud. This in turn, impacts developments in process modelling, systems, and the enterprise itself in the spirit of a digital twin. Three basic divers supporting the design-for-resilience approach are discussed next. They offer data, structure, and software environment facilitating design-for-resilience.

3.1. Manufacturing digitisation

The race for digitisation is fuelled by the same goals that manufacturing has faced in the recent decades, i.e. productivity and quality as the first order metrics. Digital manufacturing aims at creating models representing physical assets, processes, and systems. Usually these models are referred to as digital twins. The hope is that they will replicate a manufacturing enterprise to the degree of detail and accuracy needed by the applications of interest.

The progress in digitisation of manufacturing is conditioned by the availability of data and clearly articulated benefits from the modelling effort. Models of processes (logistics and physical), systems, and equipment developed at different levels of granularity and fidelity are envisioned. Many of these models will reside in a cloud.

The basic definitions, concepts, and methodologies relevant to digital manufacturing are provided in the book by Zhou, Xie, and Chen (2012). Following the concept of digital economy (Tapscott 1996) and digital earth defined in the U.S. in 1998, Xiong and Yin (2006) provided a description of digital manufacturing, including fundamental theories and technologies. Lu et al. (2020) reviewed the developments in digital twin technologies and presented a reference model. Research issues facing digital twins were identified. An open-source platform assembling tools in support of digital manufacturing was introduced in Beckmann et al. (2016). The platform was intended to democratise developments in manufacturing by offering access to many companies, from small to large. A similar solution envisioned as a toolbox to support digitisation of small and medium-size enterprises was described in Kaartinen, Pieskä, and Vähäsöyrinki (2016).

Ribeiro da Silva, Angelis, and Pinheiro de Lima (2019) identified two dozen factors enabling or preventing implementation of digital manufacturing technologies. A five-dimensional modelling approach for the development of digital twins was proposed in Zhang et al. (2019). A prototype system was developed to demonstrate performance of a reconfigurable digital-twin system built according to the modelling strategy discussed in the paper. As a step towards digital manufacturing, an approach to generate ontology from production data was presented in Huang et al. (2019).

3.2. Service manufacturing

Service orientation of an enterprise, including service manufacturing, are directly related to open manufacturing. Traditional manufacturing industry has focused on production of consumer goods (e.g. phones, cars) and industrial goods (e.g. machine tools, cranes) with a limited involvement of customers. Manufacturing has limited interactions with the end consumers whereas such interactions prevail in the service industry. Service industry does not produce goods, neither offers tangible outputs, rather it emphasises the use of knowledge to best serve customers. The differentiation between manufacturing and service industry will likely diminish in time for two major reasons. First, customers (individuals and corporations) will have more impact on the design, location, and operations of manufacturing. Second, consumer driven factors such as: (a) changing market demands, (ii) sustainability pressure, (iii) product personalisation, (iv) corporate presence in the cloud; (v) and profit maximisation will lead to sharing manufacturing resources among corporations, including the competing ones. Many manufacturing facilities will become manufacturing-as-a-service entities (Kusiak 2019a).

The linkage of service and manufacturing has been pursued for over a decade in different contexts. Feng, Sun, and He (2009) and Gao and Zhao (2012) used the term service-oriented manufacturing to emphasise integration of manufacturing and allied services.

A customer-centric view of manufacturing was emphasised. A framework combining a multi-agent system with a service-oriented architecture for the development of intelligent automation control and execution systems was proposed by Giret and Botti (2010). Helo, Phuong, and Hao (2019) discussed the requirements for scheduling as-a-service in a cloud-based environment. Service composition is central to a cloud manufacturing platform. Yuan et al. (2020) discussed details of the hierarchical structure of a cloud manufacturing service.

3.3. Cloud solutions

Cloud technology offers benefits that manufacturing cannot resist. Qian et al. (2019) designed a collaborative cloud platform for optimising production plans in additive and subtractive manufacturing. The integrated platform enhanced resource utilisation and reduced energy consumption. Zhang et al. (2019) proposed a framework for development of a cloud-based ubiquitous robotic system. The framework was demonstrated with production of a customised product. A cyber-physical manufacturing cloud was introduced in Liu et al. (2017) for direct operations and monitoring of machine tools in a manufacturing cloud over the Internet. A service-oriented architecture was developed for publication and subscription of manufacturing web services and cross-platform applications. A testbed to demonstrate remote monitoring and execution of manufacturing operations was developed. Han and Schaefer (2019) focused on eliminating a mismatch between the geometry of a part and the capability of a 3D-printer. An ontology for capturing the CAD data and 3D-printer capability was offered. A cloud-based manufacturability solution for selection of the most suitable 3D-printing capability was envisioned.

4. Digital process models in open manufacturing

The presence of open manufacturing enterprises in the cloud calls for their formal representation. Though there is no global standard for representation of enterprises, process modelling methodologies and languages are likely to be used in development of models for the manufacturing cloud.

To present a flavour of research needs of the manufacturing cloud, an algorithm for configuration of models in open manufacturing is presented. The configuration and reconfiguration may be dynamic and performed

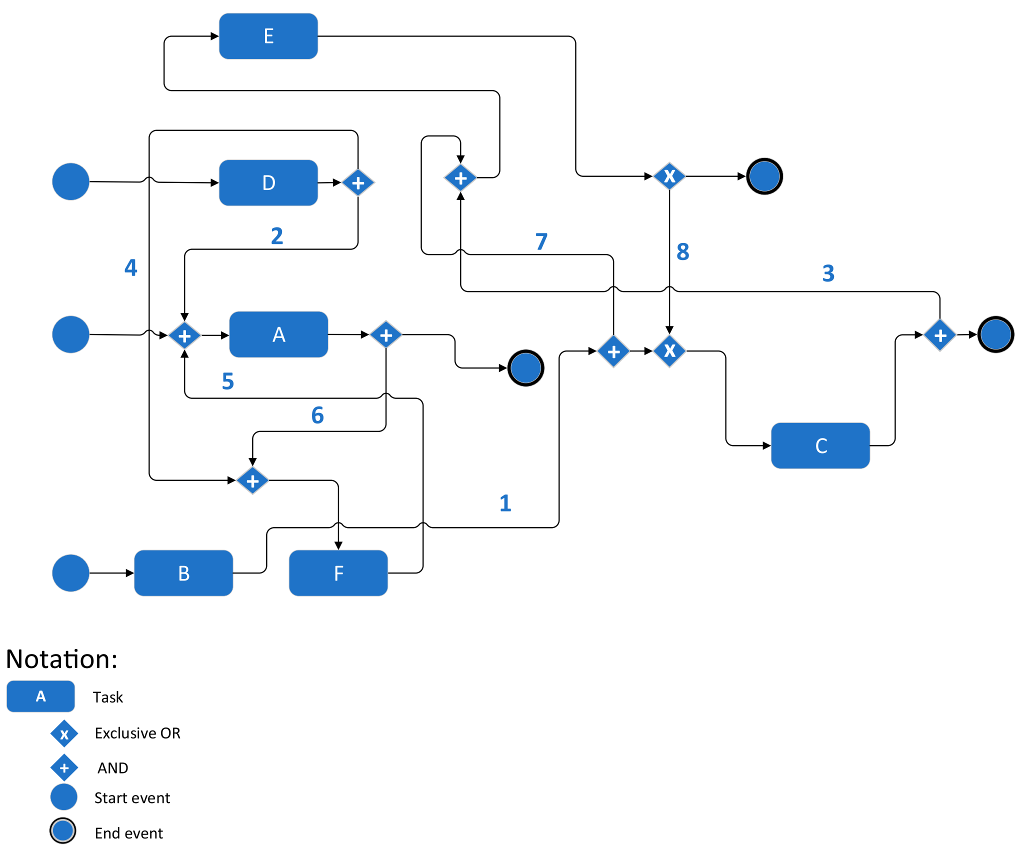

Figure 2. Digital process model of a manufacturing application.

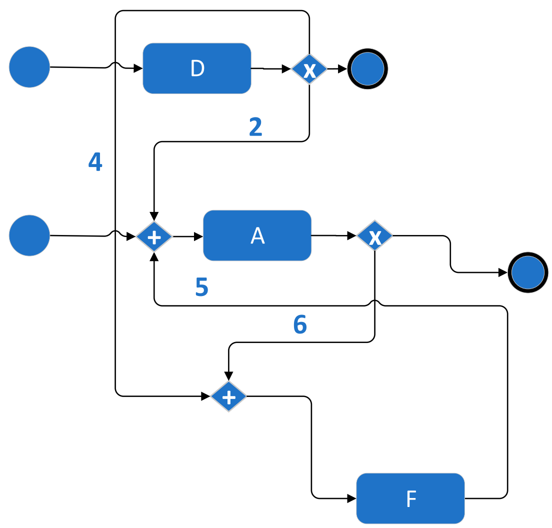

Figure 3. Digital process Model 1.

	1	2	3	4	5	6	7	8
A		*I*			*I*	*O*		
B	*O*						*O*	
C	*I*		*O*					*I*
D		*O*		*O*				
E			*I*				*I*	*O*
F				*I*	*O*	*I*		

Figure 5. Matrix representation of the digital model in Figure 2.

	2	4	5	6	1	3	7	8
D	*O*	*O*						
A	*I*		*I*	*O*				
F		*I*	*O*	*I*				
E						*I*	*I*	*O*
B					*O*		*O*	
C					*I*	*O*		*I*

Figure 6. Matrix representation of the decomposed digital model.

at different level (e.g. from an enterprise and system level to a task level) and may involve different objectives (e.g. operational efficiency, complexity reduction, visibility enhancement).

The example of a digital model presented next illustrates complexity reduction in open manufacturing.

4.1. Decomposition of digital process models

Consider the digital process model of a manufacturing application expressed with the Business Process Modeling Notation (BPMN) (details of BPMN are presented at BPMN.org). An example BPMN model is shown in Figure 2. The letters A, . . . , F denote tasks (e.g. 3D printing, assembling), while the numbers 1, . . . , 8 denote data flow between the tasks. The symbols + (AND) and X (exclusive OR) are the logical operands, while the circles denote the initiation and the conclusion events (see the legend in Figure 2).

The model in Figure 2 decomposes into Model 1 and Model 2 presented in Figures 3 and 4, respectively.

The two models are independent and each of them is less complex than the model in Figure 2, thus the complexity of the underlying process has been reduced. Decomposition of models with hundreds to potentially millions of tasks is a challenge.

For the convenience of decomposition, the model in Figure 2 is represented with the incidence matrix in Figure 5. The entry *I* in the matrix denotes Input to a task, and the entry *O* is Output from a task. For example, consider task F (row F in the matrix of Figure 5), where 4 and 6 are the inputs and 5 is the output.

The decomposition of the matrix in Figure 5 can be performed by the cluster identification algorithm (Kusiak

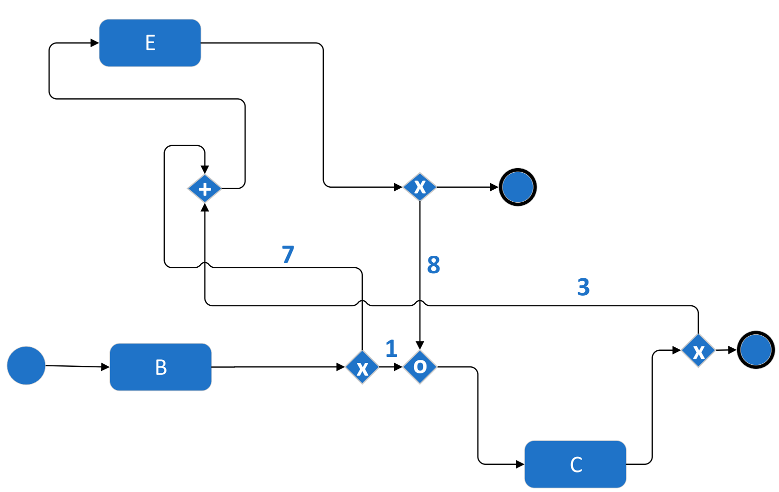

Figure 4. Digital process Model 2.

and Chow 1987). The decomposed matrix is shown in Figure 6.

The two block diagonal matrices in Figure 6 represent the models of Figures 3 and 4, i.e. the upper matrix represents Model 1, and the lower Model 2. The two matrices are mutually exclusive, which implies that the Model 1 and Model 2 are independent. The decomposition of a digital process model reduces its complexity, however, it does not impact its configuration. The model complexity algorithm introduced in the next section, performs model decomposition as well as its configuration.

5. Complexity reduction of digital process models

The complexity reduction algorithm introduced in this section generalises the cluster identification algorithm (Kusiak and Chow 1987) and the triangularisation algorithm (Kusiak, Larson, and Wang 1994).

A process complexity reduction algorithm should be able to accept data from any process modelling methodology. To meet this requirement, the process complexity reduction algorithm presented next is formulated for a graph. Such a graph can be extracted from a model implemented in any methodology, e.g. BPMN (BPMN.org), SysML (SysML.org).

Before the steps of the complexity reduction algorithm are defined, the following three definitions are introduced:

Definition 1: An *origin node* in a graph is one that that is not preceded by any other node and it has not been previously visited.

Definition 2. A *terminal node* in a graph is one that is not succeeded by any other node.

Definition 3: An *admissible node* in a graph is one that that is preceded by the previously visited nodes.

5.1. The complexity reduction algorithm

Step 1. For the current graph, identify an origin node, and (i) set the node label $i = 1$, (ii) include the node in the solution vector. Go to Step 2.

Step 2. Identify an admissible node. If admissible does not exist, go to Step 3; otherwise perform: (i) label the admissible node $i = i + 1$, (ii) include it in the solution vector, and (iii) if a node is not terminal repeat Step 2; otherwise, go to Step 4.

Step 3. Identify a cycle and merge it into a node. Go to Step 2.

Step 4. Terminate, if all nodes have been visited; otherwise, a cluster has been found: (i) record it, (ii) remove it from the initial graph, and (iii) go to Step 1.

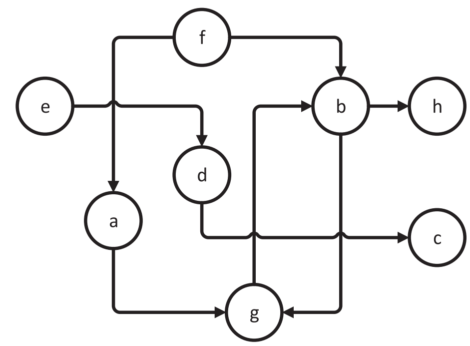

Figure 7. Process graph.

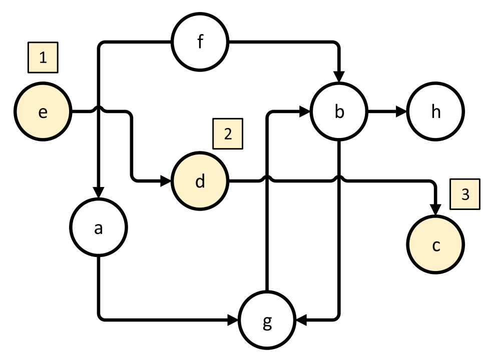

Figure 8. Partial solution 1 (the labelled subgraph): Cluster of tasks [e, d, c].

The digital model algorithm is illustrated with the example presented next. Consider the graph extracted from the digital process model of Figure 2.

The complexity reduction algorithm is illustrated next.

5.2. Illustration of the complexity reduction algorithm

Consider the graph in Figure 7 representing one of the processes of a cloud enterprise. The model includes eight tasks, a, . . . , h, with precedence constraints.

The tasks of the model in Figure 7 are:

a: Process subassembly S1
b: Inspect subassembly S2
c: Load part P on fixture F
d: Transport fixture F
e: Retrieve fixture F
f: Process subassembly S2
g: Inspect subassembly S1
h: Produce the final assembly

Iteration 1

Step 1. Node e is the origin node and it is labelled 1 (see Figure 8). Node e is included in the solution.

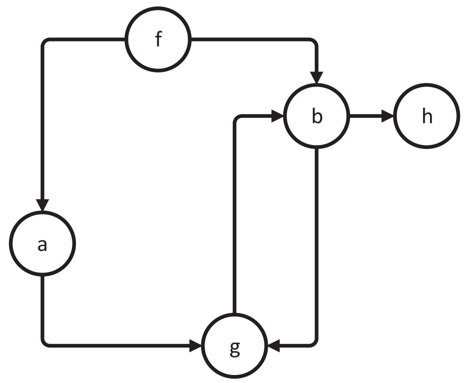

Figure 9. The graph with the cluster [e, d, c] removed.

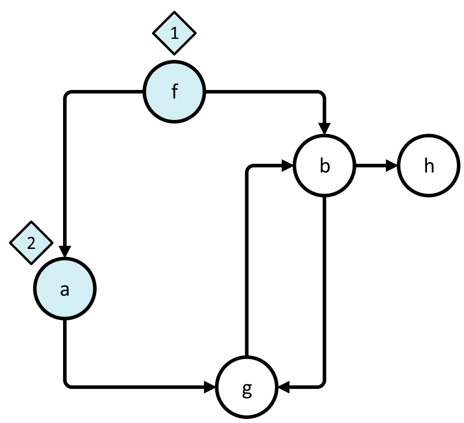

Figure 10. The graph with a cycle encountered.

Step 2. Node d is admissible, and it is labelled 2 (see Figure 8). Node d is included in the solution.

Step 3. Node c is admissible, and it is labelled 3 (see Figure 8). Node c is included in the solution.

Step 4. Since node c is terminal, cluster [e, d, c] (partial solution 1) is formed and removed from the graph is Figure 8. The resultant graph is shown in Figure 9.

Iteration 2

Step 1. Node f is the origin node and it is labelled 1 (see Figure 10). Node f is included in the solution.

Step 2. Node a is admissible, and it is labelled 2 (see Figure 10). Node a is included in the solution.

As no admissible node exists, go to Step 3.

Step 3. A cycle involving tasks g and b is identified, and merged into task (g, b) as shown in Figure 11.

Step 2. Node (g, b) is admissible, and it is labelled 3 (see Figure 11). Node (g, b) is included in the solution.

Step 2. Node h is admissible, and it is labelled 4 (see Figure 12). Node (g, b) is included in the solution.

Step 4. Since node h is terminal, the second cluster [f, a, (g, b), h] is formed.

As all nodes have been visited, the algorithm terminates.

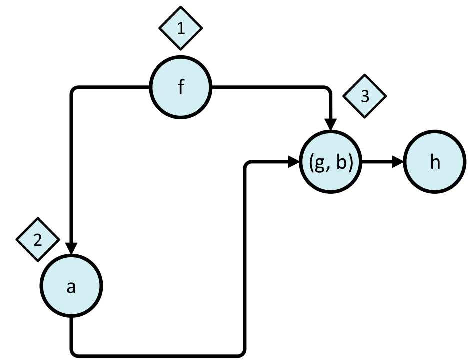

Figure 11. The graph with the cycle (g, b) merged.

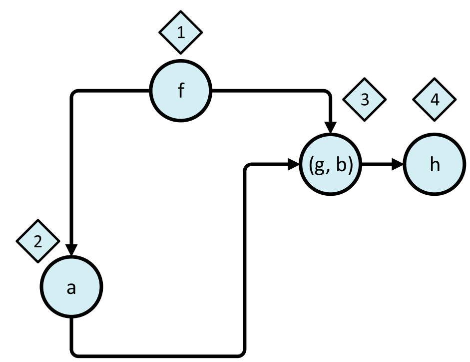

Figure 12. Partial solution 2: Cluster of tasks [f, a, (g, b), h].

The final solution made of partial solution 1 and partial solution 2 has two distinguishing characteristics:

(i) The graph shown in Figure 7 has been decomposed into two disjoint graphs represented as clusters of tasks [e, d, c] in Figure 8 and [f, a, (g, b), h] in Figure 12.
(ii) The tasks in each cluster are topologically sorted, i.e. in cluster [e, d, c], the sequence of tasks is e, d, c and in the cluster [f, a, (g, b), h], the sequence is f, a, (g, b), h. Note that the latter cluster includes a cycle.

The tasks included in each of the two clusters are listed next:

Cluster 1: Sequence of tasks
e: Retrieve fixture F
d: Transport fixture F
c: Load part P on fixture F

Cluster 2: Sequence of tasks. Note tasks g and b (shown in bold) form a cycle as they could be repeated.
f: Process subassembly S2
a: Process subassembly S1
g: **Inspect subassembly S1**
b: **Inspect subassembly S2**
h: Produce the final assembly

	a	b	c	d	e	f	g	h
a								
b	*						*	
c				*				
d					*			
e								
f	*							
g		*				*		
h		*						

Figure 13. Matrix representation of the model in Figure 7.

	e	d	c	f	a	g	b	h
e								
d	*							
c		*						
f								
a				*				
g					*		*	
b				*		*		
h							*	

Figure 14. Decomposed models of Figure 8 (Partial solution 1) and Figure 12 (Partial solution 2).

Interesting insights into the properties of the models can obtained from the matrix representation of the BPMN models. The node-node matrix in Figure 13 represents the model in Figure 7. An entry $*$ of the matrix denotes an arc between the connected nodes, e.g. $*$ with the coordinates (row c, column d) indicates an arc that is the output of node d and input to node c.

The result produced by the configuration algorithm is presented in Figure 14. The upper cluster corresponds to partial solution 1 of Figure 8 and the lower cluster represents partial solution 2 of Figure 12.

The matrix in Figure 14 is different from the decomposed matrix in Figure 6 in two ways:

(i) The matrix in Figure 6 is a node-arc matrix, while the one in Figure 14 is a node-node matrix.
(ii) The tasks in Cluster 1 are topologically sequenced [e, d, f], which is evidenced by the lower triangular shape of the upper matrix.
(iii) The tasks in Cluster 2 are topologically sequenced [f, a, (g, b), h]. The cycle (g, b) is clearly visible in the matrix in Figure 14 as it distorts the lower triangular form of the bottom matrix.

5.3. *Properties of digital process models*

Graphs or matrices representing process models can be large, e.g. involving thousands or more nodes, thus deserving to be referred to as complex. The proposed complexity reduction algorithm is useful in discovery of the properties of graphs that are discussed next.

High density property: A graph could be strongly connected or fully connected. Such graphs are usually difficult to configure without reducing their density, e.g. by removal of edges.

Low density property: Low to zero connectivity of nodes. Low density graphs offer the greatest promise of model decomposition and configuration.

Disjoint non-decomposability: A graph could decompose, however, the tasks in each cluster could not be sequenced.

Non-disjoint decomposability: A graph could be sequenced but it would not break down into clusters.

These properties are useful in getting insights into the results generated by the complexity reduction algorithm.

6. Modularity of products and manufacturing systems

Modularity is another concept supporting the design-for-resilience concept. In general, modularity reduces complexity of a system by exploiting commonality among its components. Clustering and decomposition are the primary modelling and solution approaches used in modularity. Product modularity has been widely deployed in electrical and electronics industry largely due the clear definition of functions embedded in the hardware. Modularity of mechanical products is a greater challenge as the path from the functions to their embodiment is not explicit.

Manufacturing involves equipment and systems with the latter being amenable to modularity. Modularity of the manufacturing floor in known in the literature under different names, including group technology and focused manufacturing. The growing service orientation and specialisation of manufacturing has accelerated modularity. The physical manufacturing assets can be generally represented as modules organised around common processes, functions, or hybrid systems. Here, the term module denotes the physical manufacturing assets ranging from a single machine tool through manufacturing cell to a large-scale manufacturing system.

Figure 15 illustrates a manufacturing system composed of six modules, M1 though M6. Irrespectively of the objective function used to define modularity, modular manufacturing assets are amenable to the cloud representation, e.g. in the form of process models discussed in Section 4 (see Figure 2). Ideally the content of the process description should be standardised. A process model of the physical assets would include the process description.

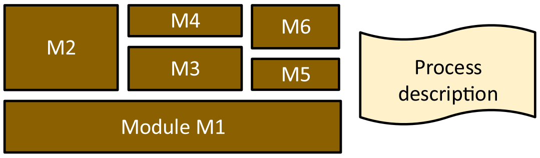

Figure 15. Modular manufacturing system.

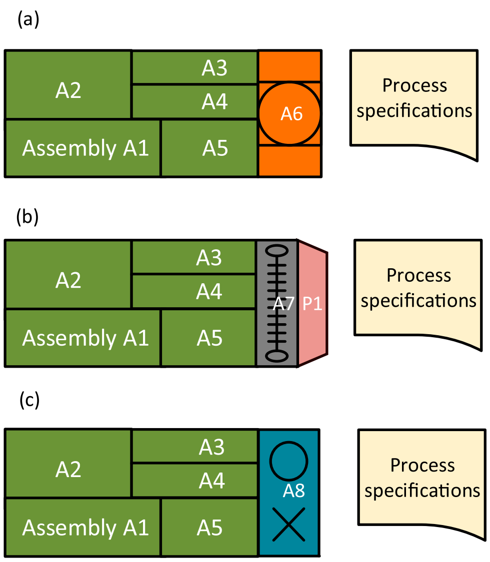

Figure 16. Delayed product differentiation of a modular product.

The modular representation of manufacturing assets is fundamental to manufacturing resilience as it allows to:

(i) keep track of module redundancy in the cloud,
(ii) assess status of each module,
(iii) identify equivalent modules when needed.

7. Delayed product differentiation

The well-known concept of delayed product differentiation supports design-for-resilience. It applies to modular and non-modular designs, though the former is preferred as it offers more product differentiation options. Product resilience comes ahead of manufacturing resilience as the latter serves the products.

The concept of delayed product differentiation is illustrated in Figure 16 where three different product variants are created by adding assemblies, A6, A7, and A8, and part P1.

The main body of the product includes assemblies A1 through A5. The product variant in Figure 16(a) was created by incorporation of assembly A6; Assembly A7 and part P1 resulted in the product variant in Figure 16(b); while the product variant in Figure 16(c) involves the differentiating assembly A8.

The delayed product differentiation supports the design-for-resilience approach by:

(i) product repurposing aiming at meeting the altered product needs while preserving the majority of the product configuration,
(ii) rapid response to the demand growth in a short time based on the inventory of the main product configuration.

8. Conclusion

Resilience of manufacturing is of paramount importance as disruptions of massive proportions ranging from pandemics to human made and natural disasters are not going away. The preferred way of handling disruptions is by minimising their impact in the aftermath. While such approach could be effective in handling local disasters, it usually does not produce good results for global disasters, such as the Covid-19 pandemic (Wuest et al. 2020). This paper advocates a design-for-resilience approach that would prepare industry to deal with adversities. The proposed approach is well aligned with the industrial transformation of growing openness, digitisation, service orientation, and cloud solutions providing data, structure, and software environment.

Open manufacturing with models of processes represented in a cloud is to enhance manufacturing visibility, including process alternatives, allowing for risk assessment and mitigation. Realising full benefits of open manufacturing, calls for digital models which benefit design-for-resilience. Modular products and processes offer build-in robustness by accounting for swapping modules across diverse products and manufacturing processes. Product differentiation strategies contribute to design-for-resilience by developing products that are amenable to serve different needs.

A complexity reduction algorithm for optimisation of digital process models was developed. The algorithm simplifies digital models and increases their interpretability. The two properties of the complexity reduction algorithm were illustrated with the graph and matrix model representations. In addition, the algorithm is suitable for models expressed with any process modelling methodology, e.g. BPMN (BPMN.org), SysML (SysML.org) and at any level of granularity, which makes it an addition to the design-for-resilience methodology.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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