Time to be Responsive in the Process Industry: A Literature-based Analysis of Trends of Change, Solutions and Challenges

Alessia Napoleone[a]*, Alessandro Pozzetti[a], Marco Macchi[a] and Rasmus Andersen[b]

[a]*Department of Management, Economics and Industrial Engineering, Politecnico di Milano, Milano, Italy*

[b]*Department of Materials and Production, Aalborg University, Aalborg, Denmark*

*now at Department of Materials and Production, Aalborg University, Aalborg, Denmark +4522569484, alna@mp.aau.dk;

+390223994752, alessandro.pozzetti@polimi.it;

+390223992726, marco.macchi@polimi.it

+4561119952, rasmus@mp.aau.dk

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The current uncertain and volatile business context is challenging firms worldwide, leading to the need to be responsive at a competitive cost. This trend is so substantial that it even affects industries traditionally competing in rather stable contexts, such as the process industry. Although the process industry includes multiple sectors with different technologies and processes, these share several aspects that make the industry as a whole distinctive to the discrete manufacturing industry. Based on a literature review, this study identifies and describes trends leading the process industry to the need for responsiveness, corresponding solutions to accommodate the need, and related challenges hindering the industrialisation and diffusion of solutions in this industry. This study shows that trends, such as the uncertainty and volatility of market requirements, are challenging the process industry to develop reconfigurability solutions across multiple production levels. The development of reconfigurability solutions is hindered by modularity, integrability, coordination and collaboration challenges.

Keywords: process industry; responsiveness; flexibility; reconfigurability; agility; lean management; literature review.

1. Introduction

Nowadays firms worldwide need to be increasingly responsive at a competitive cost. This is because of the unpredictability of market requirements and the rapid technological change in the contemporary business context. To this end, in the discrete manufacturing industry, responsiveness has become a key competitive factor for many leading firms worldwide. This phenomenon is so substantial that it can also be observed in the process industry, where productivity has traditionally been the primary competitive parameter (Crama, Pochet, and Wera 2001; Hammer and Kummer 2013).

Responsiveness is the speed at which a system can accommodate changing goals at an affordable cost (Koren and Shpitalni 2010; Mehrabi, Ulsoy and Koren 2000). The need for responsiveness is driven by the context: it is triggered by market trends (Morgan and O'Donnell 2017; Chen, Paulraj and Lado 2004; Holweg 2005), technological trends (Ahuett-Garza and Kurfess 2018), and/or social trends (Dubey, Gunasekaran, and Chakrabarty 2015).

According to the APICS dictionary, process industry refers to 'production that adds value by mixing, separating, forming and/or performing chemical reactions' (Pittman and Atwater, 2016). Examples of products manufactured by this industry are: chemicals, biotechnology, food and beverages, paper and cardboard, glass, rubber and plastics, semi-conductors, and primary metals (Lyons et al., 2013). Therefore, the process industry includes a set of heterogeneous sectors (see the classification scheme proposed by Abdulmalek, Rajgopal and Needy (2006)), due to clear differences in technological processes. However, analysing their general characteristics, many common and interconnected aspects can be highlighted, especially for those process sectors for which the point in the process at which the switch from continuous operations (where no discrete units are produced) to discrete operations (performed on single or groups of units, such as assembly and packaging) happens late in the process (Abdulmalek, Rajgopal, and Needy 2006). For this reason, this study only considers the latter, which are the most representative sectors of the process industry; these sectors are: cement, glass, steel and metal, chemical (including, for example, pharmaceutical, cosmetics, soap and paint) oil and gas, paper and pulp; leaving aside sectors such as the textile, for which non-discrete units become discrete relatively early in the process. The common aspects of the most representative sectors of the process industry are summarised as follows.

Firstly, production processes are highly complex from a technological perspective. Typically, a very high number of process parameters must be controlled to fulfil required quality standards. Due to technology and product characteristics, firms within the process industry are typically subject to severe economies of scale, resulting in two main consequences: (i) the exploitation of plants and machines with typically very high production capacity and efficiency and (ii) the need to make extensive investments in process equipment and plants. To justify such investments, the life cycle of process plants is often several decades. Due to technological complexity, changeover times can be long and expensive. Therefore, process plants are traditionally run with large batches, resulting in low variety of offered products (i.e. little customization and differentiation). To spread the high capital investments on the largest possible amount of finished products, plants are typically operated twenty-four hours a day and seven days a week. Producing in a continuous way, avoiding stoppages, makes maintenance very critical.

These common characteristics makes the process industry distinctive to the discrete manufacturing industry and leads the former to be inherently less prone to responsiveness. This is also evident from the literature on the subject which, unlike literature related to the discrete manufacturing industry, is sparsely investigated. To understand the changes in the process industry, this literature review investigates different sectors within this industry, to derive general observations that can be synergistically valuable for multiple sectors of the process industry. More precisely, the objective of this study is answering the following three research questions:

1) What are the context-driven trends leading the process industry to the need for responsiveness?

2) What solutions are proposed to allow the process industry to improve responsiveness, thus accommodating the context-driven trends?

3) What are the challenges hindering the industrialisation and diffusion of solutions to improve responsiveness in the process industry?

The three research questions are progressively addressed in different sections of this study. After framing the adopted research methodology in Section 2, Section 3 identifies and describes trends leading the process industry to the need for responsiveness, in relation to the first research question. Next, Section 4 identifies, describes, and classifies proposed solutions to accommodate these trends, thereby answering the second research question. Answering the third research question, Section 5 identifies, describes, and classifies challenges related to the industrialisation and diffusion of solutions in the process industry. Finally, Section 6 draws the conclusions of the study.

2. Research methodology

A structured literature review was conducted to achieve a comprehensive overview of the change towards responsiveness affecting firms within the process industry. Considering the peculiarities of the operations management field compared to other fields, the guidelines provided by Durach, Kembro, and Wieland (2017) were followed as detailed throughout this section. The methodology adopted for this literature review is comprised of five stages, including:

i. identification of literature review scope;
ii. collection of literature sample;
iii. selection of pertinent literature;
iv. analysis of literature;
v. report of the results.

In stage one, the scope of the research was identified through a pilot literature review of responsiveness in the process industry. At this first stage, a reference to the responsiveness-related theory developed in the discrete manufacturing industry was made, since this is a widely researched topic compared to responsiveness in the process industry. According to discrete manufacturing-related literature, responsiveness can be achieved through flexibility and reconfigurability solutions (Santos Bernardes and Hanna 2009; Mehrabi et al. 2002; Daugherty and Pittman 1995; Shaik, Rao and Rao 2014):

In stage two, the sample of literature potentially relevant was identified. The search databases used for the investigation are Scopus and Web of Science. Literature was searched by title, abstract and keywords. To ensure the coverage of the research questions, key terms related to the topic such as “process industry” and “responsiveness” were included in the search string. Specifically, the search string was the following:

“process industry” AND (“responsiveness” OR “flexibility” OR “reconfigurability”)

Furthermore, as many contributions treated agility (Abdelilah, Korchi, and Balambo 2018; Yusuf et al. 2014a; Garbie 2011) and lean management (Abdulmalek and Rajgopal 2007; Hodge et al. 2010; Lyons et al. 2013) as solutions to achieve responsiveness, an additional search string was considered as follows:

“process industry” AND (“agility” OR “lean”).

In stage three, the pertinent literature was selected by applying appropriate inclusion and exclusion criteria to the identified sample. The criteria were:

- Only contributions written in English language were reviewed.
- To ensure reliability and validity of the findings, theoretical, empirical, and review papers were considered, filtering by journal papers as primary studies.
- To ensure an answer to the three research questions with respect to current changes, a time frame from 2010 to 2021 was considered.

By applying the aforementioned criteria, 116 contributions were identified.

To further select literature, the abstracts of the studies were analysed. Only contributions explicitly mentioning trends of change, solutions to accommodate such trends, or challenges related to these trends were selected Moreover, only contributions addressing the process industry in general, or focusing on those sectors most representative of the process industry were selected, as argued in Section 1. Through this process, 35 contributions relevant to this study were selected. Furthermore, through a backwards reference search strategy (Levy and Ellis 2006), 16 additional studies were selected based on the same criteria.

In stage four, the combined sample of 51 relevant contributions was thoroughly analysed. The selected studies were labelled according to the specific process industry sectors (e.g. pharmaceutical, steel, oil and gas, etc.) they refer to and coded in an Excel database. The Excel database includes a review template to facilitate a structured analysis of “why” and “how” the selected literature was considered relevant to answer to the research questions formulated for this study.

The appended Table A1 provides further methodological transparency by detailing whether contributions supported this study to identify (i) trends of change; and/or (ii) related solutions; and/or (iii) related challenges.

In the selected literature sample, 17 contributions provided information about the geographical scope and a majority (seven contributions) had their geographical scope in Europe. Specifically, one of them referred to Europe as a whole, while the remaining focused on specific countries in Europe, i.e. two of them in the UK, and the others taking outset in Croatia, Germany, Denmark and Sweden. Four contributions had their geographical scope in North America. Another four contributions had their geographical scope in Asia; specifically, two of them in India and the remaining two contributions in

Oman, and China. Finally, one contribution had Russia as its geographical scope, and one contribution took outset in Africa, specifically in Libya.

In the last stage, the results of the review were reported, as described in the following Sections 3, 4, and 5.

3. Context-driven trends leading the process industry to the need for responsiveness

Traditionally and aside from possible exceptions, the process industry has competed in a rather stable business context (Crama, Pochet, and Wera 2001; Hammer and Kummer 2013). However, as argued in this section, such context has changed dramatically. This section identifies and analyses the context-driven trends leading the process industry to the need for responsiveness, thereby addressing the first research question.

Based on the selected literature, eight trends of change in the process industry are identified. These trends are leading such industry to the need for responsiveness as they emphasise the need to: (i) produce according to new and unpredictable market requirements, (ii) accommodate technological changes, and (iii) satisfy social and environmental requirements. The identified context-driven trends are:

i. market globalisation and competition;
ii. request for differentiated products;
iii. shift to specialties/niche markets and to customisation;
iv. importance of customer service level;
v. uncertainty of product lifecycles and required volumes;
vi. process innovation and technology pressures;
vii. environmental and sustainability issues;
viii. pressure to reduce costs.

A complete overview of the analysed literature, reporting focused process industry sectors, and identified trends can be found in the appended Table A2. In the remainder of this section, these trends (subsequently identified by the abbreviations T1 through T8) have been described based on literature.

- **T1. Market globalisation and competition.** Market globalisation and consequent global competition in the process industry is discussed by multiple contributions (appended Table A2). According to literature, market globalisation and competition is stimulating several other trends that lead the process industry to the need for responsiveness, such as: the shortening of product life cycles (Ladiges et al. 2018); market fluctuations and great variation in consumer preferences (Ladiges et al. 2018); the need to improve customer service level (Liu and Papageorgiou 2013); the need to be more efficient (Liu and Papageorgiou 2013); and the need to innovate adopted technologies (O'Mahony et al. 2016).
  Thus, T1 appears as an overall trend, influencing several of the remaining eight trends.
- **T2. Request for differentiated products.** Many contributions (appended Table A2) addressed the need to face an increasing request for differentiated products in the process industry. For example, some contributions expressed the need to increase and manage the variety of products to improve their individualisation and the diversification of markets through process innovation (Buchholz 2010; LaForce 2016; Ozgur Unver 2011). As anticipated in Section 1, to increase the variety of products and avoid incurring in long changeovers, process innovation is needed, as traditionally process plants are highly complex and expensive, leading to the need to produce in large batches.

- **T3. Shift to specialties/niche markets and to customisation.** In the analysed sample, only four contributions referred to T3 (appended Table A2). However, already in 2001, Crama, Pochet and Wera (2001) observed that an increasing number of process industry sectors (even traditional "heavy" sectors like the steel industry) were shifting to specialties markets. Indeed, these sectors no longer restrict themselves to commodity products, but also attempt to customise their products and move toward specific market niches with higher profit margins (e.g. pharmaceutical or specialty chemicals). More recently, Yang, Vyatkin and Pang (2014) referred to the necessity for process industry sectors to produce small quantities of many customised products rather than mass production of a single or few products.
- **T4. Importance of customer service level.** Customers of process industry sectors are more and more demanding (Wilson 2018) and only customer-oriented firms, which recognise and respond timely to customer requirements, can be competitive (Stefanić, Tošanović, and Ćala 2010). Furthermore, Stefansson, Jensson, and Shah (2009), referring to the pharmaceutical sector, pointed out that providing high service level is one of the key factors to succeed. In the chemical sector, Hammer and Krummer (2013) stressed the importance of customer service level. To improve this parameter, they suggested to act on availability, flexibility, and reliability of the production system. In the steel sector, the importance of improving reaction speed to the market of the whole supply chain was observed by Zhang, Xu and Dong (2012).
- **T5. Uncertainty of product lifecycles and required volumes.** Many authors (appended Table A2) remarked the increasing uncertainty of product lifecycles and required volumes in process industry sectors. T5 is a very interesting trend,

considering that traditionally, and aside from possible exceptions, the process industry has competed in a rather stable business context (Crama, Pochet, and Wera 2001; Hammer and Kummer 2013).

- **T6. Process innovation and technology pressures.** Technology changes represent factors contributing to uncertainty and unpredictability in all process industry sectors, leading to the need for the ability to adapt to unexpected changes (Nedhish, Sabu and Krishnankutty 2015). To this end, Lier, Wörsdörfer and Gruenewald (2016) pointed out that new modular concepts in process technology promise better adjustment to dynamic conditions. Moreover, process industry sectors should move towards the development of an information technology infrastructure following seamlessly market changes (Greppi 2010).
- **T7. Environmental and sustainability issues.** Sensitivity to environmental and sustainability issues is a critical aspect in several contributions (appended Table A2). As already pointed out in 2007 by Jamsa-Jounela (2007), process industry sectors should identify and develop new sustainable environmental and energy solutions to accommodate challenges such as climate change and increasing scarcity of raw materials.
- **T8. Pressure to reduce costs.** The pressure to reduce costs is a well-recognised trend for the process industry. Compared to other trends, T8 has always been a requirement for the process industry, as also reported in Section 1. Nowadays, considering all other trends described in this section, T8 keeps its relevance and challenges the process industry as it has to be addressed in combination with very different trends that might potentially lead to cost increases.

This section has provided an answer to the first research question. Table 1 condenses the results by showing the relationship between the nine trends and the different process industry sectors identified.

Table 1 Summary of the literature referring to the eight trends leading the process industry to the need for responsiveness sorted by sectors

Sector	T1	T2	T3	T4	T5	T6	T7	T8
Cement	1	-	-	1	-	-	-	1
Chemical	5	3	2	-	5	2	5	5
Oil and gas	1	-	-	1	2	-	1	3
Paint	1	-	-	1	-	-	-	-
Pharma	2	2	-	1	-	1	1	-
Process (general)	11	8	2	4	13	3	1	4
Steel	1	-	-	-	-	-	-	2
Total	**22**	**13**	**4**	**8**	**20**	**6**	**8**	**15**

Table 1 illustrates that the three trends, T1 (market globalisation and competition), T5 (uncertainty of product lifecycles and required volumes), and T8 (pressure to reduce costs) are the most frequently identified trends, with T1 appearing in almost half (49 percent) of all the selected contributions. The prevalence of T1 is justified by the fact that it appears as an overall trend, thereby influencing the others. The frequent reference to both T5 and T8 shows that firms need to be increasingly market-driven, challenged by the uncertainty and volatility of market requirements (T5), without losing sight of costs, thus developing efficient solutions (T8).

4. Solutions allowing the process industry to improve responsiveness

The existence of the trends of change identified in Section 3 leads the process industry to the search for solutions to improve responsiveness. This section begins by further elaborating on flexibility and reconfigurability solutions to improve responsiveness. Indeed, both flexibility and reconfigurability solutions allow proactive adaptation of firms to changing requirements (Azab et al. 2013), thus proactively leveraging – instead of suffering – the trends of change identified in Section 3. Then, the second research question is addressed since solutions proposed in literature are gathered and categorised.

As argued in Section 1, in the past two decades, scientific literature (referring to manufacturing in general) has suggested the adoption of flexibility and reconfigurability solutions to enable firms' responsiveness (Santos Bernardes and Hanna 2009; Mehrabi et al. 2002; Daugherty and Pittman 1995; Shaik, Rao and Rao 2014).

- Flexibility is the capability of a manufacturing system to 'change status within an existing configuration of pre-established parameters' (Santos Bernardes and Hanna 2009). More completely, to Das (2001), flexibility is the ability of a system to change states across an increasing range of volume and/or variety, while adhering to stringent time and cost metrics.
- Reconfigurability is the capability of a manufacturing system to quickly respond to both predicted and unpredicted market changes through the adoption of different configurations (Eldardiry et al. 2012). In other words, it allows the system to repeatedly change or rearrange its components in a cost-effective way to address environmental and technological changes (Setchi and Lagos 2004; Abdi 2009). Reconfigurability has been widely studied within literature focused on discrete manufacturing (for instance, see Koren (2013); Niroomand, Kuzgunkaya and Bulgak (2014)). It is generally accepted that reconfigurability can be decomposed into six core characteristics that are modularity, integrability, diagnosability, scalability, convertibility, and customization (Koren 2013; Hasan, Jain and Kumar 2014).

Flexibility can be considered a short-term solution to leverage trends of change, defined within a given time. Flexibility solutions require a reasonably small effort and allow a limited set of actions (within a predetermined range of change) (Terkaj, Tolio and Valente 2009; Azab et al. 2013).

Conversely, reconfigurability is a medium and long-term solution to leverage trends of change. It allows dynamic changes of the production system over time (Stoian and Frumuşanu 2007). Unlike flexibility, reconfigurability actions require higher but adequate effort (in terms of reasonable times and low costs) in order to allow any change (thus, not within a predetermined range of change).

In the following sub-sections, proposed flexibility and reconfigurability solutions in the process industry are analysed. To facilitate categorisation of the solutions they are sorted according to the production level they address. There are several production levels of a firm to which the concepts of reconfigurability and flexibility can be associated (Andersen, Brunoe and Nielsen 2015; Wiendahl et al. 2007). In this study, four levels are considered: machine (i.e. individual production phase), system (e.g. lines or production departments), factory (i.e. the whole plant including multiple systems and the entire logistics system), and network (i.e. supply chains).

Depending on the production level, solutions might differ. Indeed, according to some authors, solutions at lower levels mainly presuppose structural changes, while at upper levels they might also include managerial changes (Ayman, Youssef, and ElMaraghy 2006; Bi et al. 2008; Andersen, Brunoe, and Nielsen 2015; Napoleone et al. 2019). For this reason, solutions are also classified as structural or managerial. Structural solutions are related to physical aspects of: (i) production system and/or network configuration, or (ii) the Information and Communication Technology (ICT) infrastructure such as information and decision support systems supporting the production system and/or network. Managerial ones are related to methods, techniques, or criteria for the management of the production system and/or network.

4.1 Flexibility solutions

The literature proposing flexibility solutions is summarised in the following Table 2. Table 2 also reports the level of implementation of proposed solutions in the industry. In general, flexibility solutions aim to accommodate a general increase of product variety, without compromising the service level required by the market. The studies listed in Table 2 mainly aim at improving customer service level and operational efficiency (Hokoma, Khan and Ussain 2010; Hammer and Krummer 2013; Liu and Papageorgiou 2013; Panwar et al. 2015; Saranen et al. 2010; Panwar et al. 2018). Some studies also focus on reducing lead times (Hammer and Krummer 2013), reducing changeover times (Štefanić, Tošanović and Ćala 2010), or increasing mix flexibility (Wilson and Ali 2014).

Table 2 Flexibility solutions according to literature (ordered by production level of interest)

Level of interest	Reference	Kind of solution	Sector	Implementation in industry
Machine	Wilson 2018	managerial	process (general)	case study
System	Vieira, Pinto-Varela and Barbosa-Póvoa 2015	managerial	process (general) and paint	case study
	Wilson and Ali 2014	managerial	process (general)	case study
Factory	Chowadary and George 2011	managerial	pharma	case study
	Hokoma, Khan and Ussain 2010	managerial	steel	industry survey
	Lyons et at. 2013	managerial	process (general)	industry survey
	Panwar et at. 2015	managerial	process (general)	literature-based general guidelines
	Panwar et at. 2018	managerial	process (general)	industry survey
	Štefanić,Tošanović and Ćala 2010	managerial	process (general)	case study
Network	Liu and Papageorgiou 2013	managerial	process (general)	numerical example
	Saranen et al. 2018	managerial	metal	case study

A description of the identified flexibility solutions is provided below, according to the production levels of interest. To synthesize the results, solutions are grouped in two supersets. The first superset includes solutions at the machine, system, and factory levels; the second superset includes solutions at the network level.

- **Flexibility solutions at the machine, system, and factory levels.**

  At the machine and system levels, specific solutions regarding scheduling issues were provided. Wilson and Ali (2014) applied a sequencing coordination mechanism (where similar products are grouped together to run consecutively in a production schedule) to the final stage of a process (packaging of the product) in a case study as a way to achieve operational mix flexibility in process industry sectors. Vieira, Pinto-Varela and Barbosa-Póvoa (2015) provided mathematical formulations to improve the daily process schedule, with special emphasis to the production output, resources availability and optimisation of the required manpower at a paint firm.

At the factory level, the contributions listed in Table 2 emphasized the use of lean practices and total quality management tools to improve operational performances, leading to better flexibility, and accommodating the service level required by the market. For example, Chowadary and George (2011) assisted a pharmaceutical firm in reducing lead times, cycle times and work-in-process inventory, by implementing the value stream mapping, thus eliminating unnecessary inventory and setup times and leading to significant improvements in on-time delivery.

- **Flexibility solutions at the network level**

  At the network level, both the contributions in Table 2 explicitly addressed customer service level and cost effectiveness as relevant goals for global supply chains. Saranen et al. (2010) analysed transportation strategies in Russian firms and referred to the forthcoming need in the metal sector to change paths according to changing demand requirements so to increase customer service level. Liu and Papageorgiou (2013) addressed production, distribution and capacity planning of global supply chains considering cost, responsiveness and customer service level simultaneously.

It appears remarkable that the majority of methodologies adopted in the studies summarised in Table 2 are surveys or case studies focused on actual firms and whose results are supposed to be generalised to certain countries or sectors. The adoption of this kind of approach in literature confirms the rather wide diffusion of flexibility solutions within the industry. Moreover, scientific literature proposes mainly managerial solutions of flexibility, often consisting of the implementation of lean practices (Štefanić, Tošanović and Ćala 2010; Wilson and Ali 2014; Hokoma, Khan and Ussain 2010; Chowadary and George 2011; Panwar et al. 2015), allowing great benefits in terms of customer service level and operational efficiency. On the other hand, literature has generally not focused on structural solutions. In fact, structural solutions of flexibility can no longer be considered innovative today: most of them (e.g. automated solutions offering low setup times) are already commercially consolidated (already offered by the best technology providers).

4.2 Reconfigurability solutions

The literature offering reconfigurability solutions mainly addresses the challenging trend of dealing with uncertainty and volatility of market requirements.

As was done for flexibility solutions, reconfigurability solutions are summarised in the following Table 3, reporting production levels of interest, kind of solution (structural and/or managerial) and the level of implementation in industry.

Table 3 Reconfigurability solutions according to literature (ordered by production level of interest)

Level of interest	Reference	Kind of solution	Sector	Implementation in industry
Machine	Adamo et al. 2016	structural	pharma	prototype
	Greppi 2010	structural	chemical	prototype
	Müller, Lier and Grünewald 2015	structural	process (general)	prototype
	Yuan, Ge, and Song 2016	structural	chemical	numerical example
System	Lepuschitz et al. 2018	structural	process (batch)	none (conceptual model)
	Ozgur Unver 2011	structural	pharma	prototype
Factory	Wan et al. 2018	structural and managerial	pharma	prototype
Network	Munoz et al. 2015	structural and managerial	process (general)	literature-based case
	Zhang, Xu and Dong 2012	structural and managerial	steel	case study
	Yusuf et al. 2014a	structural and managerial	oil and gas	industry survey
	Yusuf et al. 2014b	structural and managerial	oil and gas	industry survey
	Wikner and Noroozi 2016	structural and managerial	process (general)	case study

A description of the reconfigurability solutions is provided below according to the production levels of interest. Analysed solutions are grouped in two supersets. The first superset includes solutions at machine, system and factory levels while the second superset comprises solutions at network level. Indeed, as also reported in Table 3, network solutions have different nature than those at lower production levels, as these are mainly managerial solutions and are relatively diffused in industry.

- **Reconfigurability solutions at machine, system and factory levels**

  At these production levels, to face the uncertainty and volatility of market requirements, the literature argues that solutions should incorporate modularity and integrability as reconfigurability characteristics. The modularity characteristic enables easy reconfigurations of production units to meet evolving requirements. Building both on adaptable ICT and plant control architectures, the integrability characteristic supports the integration of heterogeneous systems

  To address demand volatility, Adamo et al. (2016) developed a reconfigurable manufacturing platform as an alternative approach to batch processing in the pharmaceutical industry. An important characteristic of the proposed solution is modularity: production units are arranged in modules to enable reconfiguration to produce four different drug products within the same system. Accordingly, Müller, Lier and Grünewald (2015) developed a modular absorption column as a promising approach for the implementation of multiphase processing into a reconfigurable production system, which can be easily scaled up by numbering-up the modules to the target throughput.

  To Greppi (2010), as the process industry is challenged by the need to react quickly to market changes, the process automation and information technology infrastructure should allow adaptation to changes, without requiring frequent reconfiguration or manual adaptation of customised interfaces. To this end, Greppi referred to OPC UA as a promising communication protocol enabling data exchange between heterogeneous systems, thus enabling interoperability in industrial automation. As industrial plants undergo different kinds of change, Yuan, Ge and Song (2016) improved the adaptability of an individual process by developing an adaptive sensor model.

In the pharmaceutical industry, Ozgur Unver (2011) presented system architectures that make “high throughput screening” (i.e. a function to deliver new drugs rapidly and cost effectively) more reconfigurable. To this end, in their control architecture, they developed a modular and object-oriented control-system framework. Wan et al. (2018) propose a data-driven reconfigurable factory for pharmaceutical production to accomplish functionality reconfiguration and flexible scheduling of manufacturing resources in a more and more dynamic market. The solution relies on the IEC 61499 standard, which ensures the modularity and integrability of the automation systems (Thramboulidis 2012).

- **Reconfigurability solutions at network level**

  At this production level, the uncertainty and volatility of market requirements are addressed with solutions incorporating: (i) characteristics of collaboration/cooperation and information sharing, and (ii) characteristics of reconfigurability such as modularity and integrability. It is worth remarking that solutions at this production level have been often associated to the concept of agility, rather than reconfigurability, in literature: relying on collaboration/cooperation and ICT to quickly share data between stakeholders, agile networks can respond to volatile fluctuations in market requirements (Zhang, Xu and Dong 2012; Yusuf et al. 2014a and 2014b).

Yusuf et al. (2014a and 2014b) investigated the level of adoption of solutions to respond and adapt to a business environment characterised by dynamic and continuous change within the oil and gas networks. They showed that high percentages of firms indicate high adoption of levers such as 'cooperating to compete' and 'leveraging impact of people and information'. Wikner and Noroozi (2016) proposed an approach based on standard modules that, through configuration, generates customised network design.

Zhang, Xu and Dong (2012) designed and implemented a supply chain information sharing platform based on Service-Oriented Architecture and Web Services. Their platform is an enabler of reconfigurability as it provides a solution of the standard data structures and communication methods between steel manufacturers and external systems. Indeed, their solution is an enabler of collaboration along the supply chain.

Munoz et al. (2015) developed an approach for supply chain planning and scheduling integration of a process industry firm. To do so, they also provided a platform for solving the problem of integration, standardisation, and compatibility of heterogeneous modelling systems. In other words, they also provided a solution (i.e. the platform) as enabler of integrability between different modelling systems, supporting the managerial activity of planning and scheduling.

In general, managerial solutions are mainly found to be applied at higher production levels while structural ones are found at lower production levels (see Table 3). This is compliant with observations made by some researchers with regard to the discrete manufacturing industry: reconfigurability at lower levels is principally obtained through structural (e.g. physical) changes, while at upper levels it is obtained through soft (e.g. managerial) changes (Bi et al., 2008; Ayman, Youssef and ElMaraghy, 2006;

Andersen, Brunoe and Nielsen, 2015). Complementarily, some researchers asserted that 'reconfigurability at lower production levels' positively influences 'reconfigurability at upper production levels' (see Bruccoleri et al. 2005; Andersen, Brunoe and Nielsen 2015; Napoleone, Pozzetti and Macchi 2018). This is also evident in the outcomes of the present literature-based analysis in process industry: managerial solutions of reconfigurability (such as collaboration/cooperation and information sharing) are enabled and positively influenced by structural solutions (such as modular organizational structures as well as integrability of information systems).

It is remarkable that most of the aforementioned studies (excluding those at network level) proposed innovative solutions in the form of prototypes. In terms of Technology Readiness Levels, which is a measure suggested by the ISO 16290 (2013) for estimating technology maturity of solutions, compared to the flexibility solutions analysed in section 4.1, reconfigurability solutions have lower Technology Readiness Level.

4.3 Discussion on the flexibility and reconfigurability solutions

Section 4 provides an answer to the second research question by analysing solutions of flexibility and reconfigurability that have been proposed in literature. The latter are far less diffused among firms as adoption is generally low; nevertheless, to accommodate the trends identified in section 3.2, solutions of reconfigurability are considered more suitable. The difficulty in implementing these solutions is also confirmed by the fact that reconfigurability presupposes the presence of structural characteristics of modularity and integrability. While this might seem obvious – but still challenging – in the discrete manufacturing, it is even more challenging in the process industry. Properly managed, structural characteristics allow firms in the process industry to face the uncertainty and volatility of market requirements in an efficient way.

5. Challenges hindering the industrialisation and diffusion of solutions to improve responsiveness in the process industry

To complete the analysis of the process industry, this section addresses the third research question.

Unlike the previous section on solutions to accommodate the context-driven trends of change (Section 4), this section analyses challenges hindering the industrialisation and diffusion of the solutions analysed in the previous section. Indeed, this section is a collection of studies envisioning how process industries should develop in future, also including some of the concluding remarks of the analysed literature sample.

5.1 Structural and managerial challenges

Similarly to how solutions were categorised in Section 4, the challenges identified in the literature are classified as:

- structural challenges (related to either (i) physical characteristics of production system and/or network configuration, or (ii) the ICT infrastructure such as information and decision support systems supporting the production system and/or network), or
- managerial challenges (related to methods, techniques, and criteria for the management of the production system and/or network).

From the structural perspective, challenges (subsequently identified by the abbreviations S1 through S4) are described below.

- **S1. Innovation of production processes by means of modular technology.** This challenge relates to making production processes adaptable to changes, as if they were Lego bricks (Buchholz 2010; Müller, Lier and Grünewald 2015; Becker et al. 2016; Bloch et al. 2017). Indeed, according to Lier, Wörsdörfer and Gruenewald (2016), transformable production systems in process industry firms would allow adaptability to dynamic contexts thanks to their modular design.

- **S2. Adaptation of control architectures.** Some authors referred to the challenge for firms in the process industry to implement distributed control using, for example, the agent-based technology (Yang, Vyatkin and Pang 2014; Lier, Wörsdörfer and Gruenewald 2016; O'Mahony et al. 2016). Indeed, agent-based architectures would enable scalability, adaptability, and robustness of processes in dynamic and uncertain environments (Gao et al. 2013). Ozgur Unver (2011), focusing on the pharmaceutical sector, demonstrated the need for software architectures designed to accommodate future changes. To the author, modularity of software architectures could enable rapid reconfigurations and could be obtained by practicing object-oriented design and programming principles. Fragapane et al. (2020) pinpointed digitalisation of material flows and decentralisation of control architectures as enablers of adaptive production systems.
- **S3. Development and improvement of information sharing platforms.** The development and improvement of information sharing platforms is a challenging aspect for firms in general and it is even more challenging in the process industry. It requires standardisation for data, application, and process integration to facilitate data exchange between firms along the supply chain (Hosseini and Helo 2012; Zhang, Xu and Dong 2012; Munoz et al. 2015; Bogle 2017).
- **S4. Development of decision support systems as structural tools to improve decision making.** New decision support systems should be designed to face the challenge for the process industry of managing increasingly complex and

adaptable production systems (Marques et al. 2020; Barbosa-Povoa and Pinto 2020). For example, Marques et al. (2020) recognised that the traditional structure in different decision levels does not suit new requirements as levels are too broad to capture and categorize the current mix of complex decision problems and their integration, that currently dominate the pharmaceutical industry. To them, even though IT tools, such as Enterprise Resource Planning (ERP) software, are effective in facilitating the aggregation of essential information, they do not provide optimization capabilities for effective decision-making.

From the managerial perspective, challenges (subsequently identified by the abbreviations M1 and M2) are described below.

- **M1. Development of new production planning and control approaches to deal with volatility and uncertainty.** To deal with volatility and uncertainty, new production planning and control approaches should be developed. According to Spenhoff, Semini and Powell (2016) the specific characteristics of the process industry that challenge the application of production planning and control should be properly investigated. To them, these characteristics can be classified in two opposing categories: the ones requiring the capability to deal with demand variability and uncertainty, and the ones related to production processes.

  Some authors more generically refer to the need of process industry firms to improve the coordination of resources distributed along the system and/or the network (Hammer and Krummer 2013; Lier, Wörsdörfer and Gruenewald 2016).
- **M2. Formation of strategic partnerships and collaboration.** Partnerships and collaboration should be dynamically formed and evolve to address volatile requirements (Hammer and Krummer 2013; Storm, Lager and Samuelsson 2013).

Already in 2004, Guisinger and Ghorash (2004), who focused on the chemical sector, observed that partnerships and joint ventures will increasingly allow competitiveness in the global market.

Some authors referred to challenges related to the opportunity to change kind and duration of relationships within and across firms (Garbie 2011; Lier, Wörsdörfer and Gruenewald 2013). For example, for Lier, Wörsdörfer and Gruenewald (2013) new transformable, mutable, and versatile production systems for the process industry should be developed. To them, these new production systems require new business relationships that span the whole product lifecycle. Hence, industrial engineering firms and equipment manufacturers should start offering operating services such as maintenance, repair, and overhaul. To work more efficiently and ensure short times to market, process and equipment development should increasingly merge their forces.

Storm, Lager and Samuelsson (2013) referred to the need to push towards open innovation and in-house collaborative approaches between production and Research & Development departments. Indeed, the development of new products requires adapted manufacturing technology. For this reason, according to the authors, in the process industry there is a need for interactive innovation work processes from product design through manufacturing to delivery. The importance of collaborative decision making was already stressed in 2005 by Shah (2005). To the author, process industry supply chains can be considered as distributed systems with somewhat decentralised decision-making (especially for short-term decisions) and Shah emphasised that the multi-agent-based approach is a powerful technique for simulating such systems.

5.2 Discussion on the challenges

This section provides an answer to the third research question by classifying the challenges (S1, S2, S3, S4, M1 and M2) identified in Section 5.1 in four different types related to: modularity, integrability, coordination, and collaboration. Within Table 4, the light shade of grey refers to authors addressing machine, system, and factory levels, while the dark shade of grey refers to authors addressing network level.

Table 4 Classification of challenges for the process industry with respect to modularity, integrability, coordination and collaboration

Reference	Industry sector	Modularity	Integrability	Coordination	Collaboration
Buchholz 2010	chemical	S1			
Zhang, Xu and Dong 2012	steel		S3		
Gao et al. 2013	chemical	S2	S2		
Storm, Lager and Samuelsson 2013	process (general) and steel				M2
Manenti et al. 2013	oil and gas	S1	S1		
Yang, Vyatkin and Pang 2014	process (general)	S2	S2		
Müller, Lier and Grünewald 2015	process (general)	S1			
Acar and Atadeniz 2015	process (general)			M1	
Munoz et al. 2015	process (general)		S3		
Lier, Wörsdörfer and Gruenewald 2016	process (general)	S1 and S2	S2	M1	
Bayer et al. 2017	chemical and oil and gas	S1 and S2	S2	M1	
Hohmann et al. 2017	chemical	S1	S1		
Bogle 2017	chemical		S3		
Brunaud and Grossmann 2017	process (general)		S3	M1	
Ladiges et al. 2018	process (general)	S1	M1		
Reitze et al. 2018	chemical	S1	S1		
Barbosa-Povoa and Pinto 2020	process (general)				S4
Fragapane et al. 2020	process (general)			S2	
Marques et al. 2020	pharma				S4

A description of these four types of structural and managerial challenges listed in Table 4 is provided below.

- **Modularity.** Modular processes, recurring to the use of both production platforms - shared across different product variants -, and specific modules needed to produce specific product features, are needed. The implementation of distributed control supports the exploitation and interaction of autonomous modules. Changing the fundamental structure of the network according to temporary requirements by building virtual firms (i.e. firms whose competences and know-how are virtually available to other stakeholders), supports the selection of certain partners along the supply chain as building blocks (or modules) of the overall supply chain. From another perspective, agent-based technologies can be considered modular solutions, because they are based on the use of autonomous agents.

Modularity is a challenge for the process industry because of the technological complexity of process plants and controlled process parameters, which causes high capital investments in large production plants with complex physical interactions.

- **Integrability.** To achieve greater benefit from modular structures, integrability is needed. Integrability allows the interfacing and interaction of different modules or agents in a distributed architecture. Thus, integrability also implies benefiting from adaptable software structures and information sharing platforms. From this perspective, virtual firms can easily collaborate and switch to new collaborations when facing changing needs.

  Integrability is a challenge especially because the control systems in the process industry require substantial engineering effort to integrate eventual new process modules with the remaining manufacturing system.

- **Coordination.** Modular and integrable structures are composed of distributed modules that should be opportunely coordinated. Standardised tools (such as IT solutions) and approaches to support and coordinate the decision-making process at multiple production levels are required. Thus, for example, the need for new production planning and control approaches and inventory management approaches arises.

  Coordination is a challenge because measuring all relevant key process and production system parameters involved in process plants - in an adequately short time interval – so to accordingly adapt the production system and processes based on this feedback is difficult and requires great quantities of data.

- **Collaboration**. At network level, relationships and partnerships can be considered as paramount requirements to allow process industry firms to be competitive in volatile markets. Moreover, firms could benefit from open innovation and in-house collaboration between production and Research & Development departments.

  In general, referring to either the discrete or the process industry, collaboration has always been a challenge as it requires the firm's adaptation at both organizational and operational levels.

6. Conclusions

This work presents a review of the available literature, which aims to increase the awareness – of both academics and practitioners – of trends of change leading the process industry to orient towards responsiveness, corresponding solutions, and challenges arising within this industry. More specifically, the contribution is summarised below.

- Trends of change leading different sectors within the process industry to orient towards responsiveness are identified. Uncertainty and volatility of market requirements are certainly a major trend across process industry sectors.
- Solutions to improve responsiveness to leverage the trends of change are classified in this study as flexibility and reconfigurability solutions. Reconfigurability solutions have low adoption in companies within the process industry and as a result are far less diffused in this industry, even if they are considered more suitable to accommodate the trends of change discussed in this study. The difficulty in implementing these solutions is also confirmed by the fact

that reconfigurability presupposes the presence of structural characteristics. While this might appear obvious – but still challenging – in discrete manufacturing, it is even more challenging for process industry firms.

- Challenges hindering the industrialisation and diffusion of solutions in the process industry are identified. These are described in terms of modularity, integrability, coordination, and collaboration needs. As implicitly shown in Section 5, challenges are all related to the industrialisation and diffusion of reconfigurability solutions, rather than flexibility solutions. This might indicate the need for a higher academic effort required for advancing the knowledge of how to achieve reconfigurability rather than flexibility: on the one hand, reconfigurability is suitable given the current trends of change, on the other hand, reconfigurability poses complex challenges for the process industry given its specificities.

As a review of available literature, this work collects many studies, highlighting specific aspects in different sectors included in the process industry. The purpose is to frame the state-of-the-art of research on solutions for responsiveness, to highlight issues of the process industry as a whole and favour industrial and academic research. This is relevant for both academics and practitioners. Indeed, while the available literature on the process industry has generally focused on solutions to achieve responsiveness in specific sectors (for instance oil and gas, metal, etc.), an effort to generalise the specific observations for the benefit of the whole process industry is made in this study. The managerial implications of this research revolve around the multi-sectorial value of the findings of this study. Operations managers are generally focused and specialised within their specific sectors and this study thereby supports them in gaining awareness on more general trends, solutions, and challenges driven by a common need to be responsive. This aspect should allow managers to better understand and face phenomena that are currently relevant in their industry sector by relying on guidelines and examples from other industry sectors. Thus, the possibility to disseminate knowledge across different sectors within the process industry promises to strengthen the industry itself.

This study is based on insights provided by literature. Nevertheless, additional empirical research should be carried out. The results of this research emphasise that sectorial similarities within the process industry can be reasonably found, thus additional research is justified to further investigate the relationship between production levels, managerial, and structural needs, taking outset in field evidence across industry sectors. Empirical research would be beneficial for two main reasons: (i) to provide concrete examples of application of guidelines and examples across different sectors within the process industry and (ii) to concretize the theoretical findings of this literature review so to properly engage operations managers and achieve increased receptivity to the subject.

Moreover, based on the results of this study, the available theory on reconfigurability framed in the discrete manufacturing context could likewise provide benefits in the process industry, given the necessity of facing uncertainty and volatility of market requirements.

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Appendix

Table A1 Detail of the literature analysed to support the results of this study

Authors	year	Sector	Trends	Solutions	Challenges
Acar and Atadeniz	2015	process (general)	X		X
Adamo et al.	2016	pharma	X	X	
Andersen et al.	2019	process (general)	X		X
Ataei, Panjeshahi and Gharaie	2019	chemical and oil and gas	X		
Barbosa-Povoa	2012	process (general)	X		
Barbosa-Povoa and Pinto	2020	process (general)	X		X
Bayer et al.	2017	chemical and oil and gas	X		X
Bogle	2017	process (general)			X
Brunaud and Grossmann	2017	process (general)	X		X
Buchholz	2010	chemical and pharma	X		X
Chowdary and George	2012	pharma	X	X	
Fragapane et al.	2020	process (general)	X		X
Gao et al.	2013	chemical			X
Garbie	2011	oil and gas	X		X
Greppi	2010	chemical	X	X	
Grossmann	2012	chemical	X		
Grossmann	2014	chemical	X		
Hokoma, Khan and Ussain	2010	steel	X	X	
Hohmann et al.	2017	chemical	X		X
Ladiges et al.	2018	process (general)	X		X
Lee et al.	2015	pharma	X		
Lepuschitz et al.	2018	batch process	X	X	
Lier, Wörsdörfer and Gruenewald	2016	process (general)	X		X
Liu and Papageorgiou	2013	process (general)	X	X	
Long et al.	2016	chemical	X		
Lyons et al.	2013	process (general)		X	
Manenti et al.	2013	oil and gas	X		X
Marques et al.	2020	pharma	X		X
Muller, Lier and Grünewald	2015	process (general)	X	X	X
Munoz et al.	2015	process (general)	X	X	X
Nedhish, Sabu and Krishnankutty	2015	process (general)	X		
Pancharya	2011	cement	X		
Panwar et al.	2015	process (general)	X	X	
Panwar et al.	2018	process (general)		X	
Reitze et al.	2018	chemical	X		X
Saranen et al.	2010	metal		X	
Štefanić,Tošanović and Ćala	2010	process (general)	X	X	
Storm, Lager and Samuelsson	2013	process (general) and steel	X		X
Vieira, Pinto-Varela and Barbosa-Póvoa	2015	process (general) and paint	X	X	
Wan et al.	2018	pharma	X	X	
Wikner and Noroozi	2016	process (general)	X	X	
Wilson and Ali	2014	process (general)		X	
Wilson	2018	process (general)	X	X	
Wörsdörfer, Lier and Crasselt	2017	process (general)	X		
Xuan, Pretlove and Thornhill	2018	process (general)	X		
Yang, Vyatkin and Pang	2014	process (general)	X		X
Yuan, Je and Song	2016	chemical		X	

Yusuf et al.	2014a	oil and gas	X	X	
Yusuf et al.	2014b	oil and gas		X	
Zhang, Xu and Dong	2012	steel	X	X	X

Table A2 Context-driven trends leading the process industry to the need for responsiveness (references in ascending order of date)

References	Sector	Market globalization and competition	Request for differentiated products	Shift to specialties/ niche markets	Importance of customer service level	Uncertainty of product lifecycle and required volumes	Process innovation and technology pressures	Environmental and sustainability issues	Pressures to reduce costs
		T1	T2	T3	T4	T5	T6	T7	T8
Buchholz 2010	chemical	X	X	X		X		X	X
Greppi 2010	chemical					X	X		
Hokoma, Khan and Ussain 2010	steel	X							
Štefanić,Tošanović and Ćala 2010	process (general)				X	X			
Chowadary and George 2011	pharma	X					X		
Garbie 2011	oil and gas	X							
Ozgur Unver 2011	pharma	X	X						
Pancharya 2011	cement	X			X				X
Barbosa-Povoa 2012	process (general)								X
Barbosa-Povoa and Pinto 2020	process (general)					X		X	X
Grossmann 2012	chemical	X						X	X
Zhang, Xu and Dong 2012	steel								X
Liu and Papageorgiou 2013	process (general)	X			X				
Manenti et al. 2013	oil and gas					X			X
Storm, Lager and Samuelsson 2013	process (general) and steel								X
Grossmann 2014	chemical	X						X	X
Yang, Vyatkin and Pang 2014	process (general)		X	X		X	X		
Yusuf et al. 2014a	oil and gas				X	X			X
Acar and Atadeniz 2015	process (general)	X				X			
Lee et al. 2015	pharma							X	
Müller, Lier and Grünewald 2015	process (general)	X	X			X			
Munoz et al. 2015	process (general)					X			
Nedhish, Sabu and Krishnankutty 2015	process (general)	X	X			X	X		
Panwar et al. 2015	process (general)	X				X			
Vieira, Pinto-Varela and Barbosa-Póvoa 2015	process (general) and paint	X			X				
Lier, Woersdoerfer and Gruenewald 2016	process (general) and chemical	X	X	X		X	X		X
Adamo et al. 2016	pharma				X				
Long et al. 2016	chemical							X	
Wikner and Noroozi 2016	process (general)	X				X			X
Bayer et al. 2017	chemical and oil and gas								X
Brunaud and Grossmann, 2017	process (general)	X							
Hohmann et al. 2017	chemical	X				X			
Wörsdörfer, Lier and Crasselt 2017	process (general)	X	X			X			
Ladiges et al. 2018	process (general)	X				X			
Lepuschitz et al. 2018	process (batch)					X			
Reitze et al. 2018	chemical		X			X			
Wan et al. 2018	pharma		X						
Wilson 2018	process (general)		X		X				
Xuan, Pretlove and Thornhill 2018	process (general)							X	
Andersen et al. 2019	process (general)		X			X			

Ataei, Panjeshahi and Gharaie, 2019	chemical and oil and gas							X	
Fragapane et al. 2020	process (general)		X						
Marques et al. 2020	pharma	X		X		X		X	X
		21	12	4	7	21	5	9	14