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Evaluation of Operational Resilience in Cyber-Physical Production Systems: literature review

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Abstract: In Cyber-Physical Production Systems, smart production resources (e.g., augmented operators, machines, products) can collaborate according to innovative, adaptive, and autonomous ways. This context offers new methods and tools to deal with disturbances and operational risks effectively and efficiently. In such environments, resilience engineering aims to improve the systems' abilities and capabilities to face disturbances and operational risks, and to be restored to safe behaviors, acceptable levels of performance and quality of service. Despite an increasing interest in operational resilience, and despite the importance of this topic in both research and industrial practice, there is no literature review and analysis to synthesize works and to identify the main issues encountered in this field. This article fills in this gap and shows that there are six main research streams in operational resilience.

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Keywords: Cyber-Physical Production Systems (CPPS), Operational resilience, Disturbances

1 INTRODUCTION

Production systems evolve in new technological and functional contexts and therefore have to deal with new challenges, requirements, and uncertainties. Cyber-Physical Production Systems (CPPS) rely on advances in information, communication, and automation technologies to promote the intelligence of production resources (i.e., operators, resources, robots, products), thus enabling them to collaborate and cooperate in an intelligent and adaptive way (Napoleone et al., 2020).

The high interconnectedness between smart production resources in CPPS makes them particularly vulnerable to change in its broadest sense (Mihalache et al., 2019). Disturbances can propagate through the system components. This propagation potentially creates operational risks and disturbs the continuity of production flows. It reduces productivity and cost-effectiveness and increases safety risks for production resources. The continuity of flows in supply chains (materials, energy, finance and information) can be interrupted. Consequently, this puts entire organizations

at risk, and threaten the competitiveness of both high- and low-volume production systems, both in stable production phases and in changing conditions (Bokrantz et al., 2016). As highlighted in a field survey by (Bokrantz et al., 2016), dealing with production disturbances effectively and efficiently is vital. Unfortunately, manufacturing companies are still struggling with disturbances. In the literature, several references reviewed definitions, classifications and frameworks for engineering changes and disturbance management, in complex systems in general, and in CPPS in particular (Balchanos et al., 2012; Colombo et al., 2016; Wied et al., 2020).

In the context of a CPPS, the concept of resilience has been put forward to refer to the ability of a system to withstand disturbances through maintaining system functions and structures, reducing the magnitude/duration of disturbed states, and/or responding to disturbing events/situations (Moghaddam and Deshmukh, 2019a). This paper focuses on the concept of “operational resilience”, defined as the ability of a CPPS to respond to, and recover from,

disturbances and operational risks (McFarlane et al., 2018). The objective is to provide and maintain an acceptable/tolerable/satisfactory level of performance and quality of service in the face of various types of disturbances and operational risks threatening preset organization (e.g., operations management) and expected performance. Despite an increasing interest in operational resilience, and despite the importance of this topic in both research and industrial practice, there is no literature review and analysis to synthesize works and to identify the main issues encountered in this field. This article fills in this gap and reviews works on the evaluation and assessment of operational resilience. Therefore, the paper is structured in five sections. Section 2 presents the methodology for the literature review. Section 3 analyzes the so identified references. Section 4 discusses the literature review results. Finally, Section 5 concludes the paper and provides future research directions.

2 RESEARCH METHODOLOGY

Resilience is a cross-disciplinary field of study, that has been investigated according to several directions, with respect to a multitude of viewpoints, and applied to numerous types of systems. In CPPS, resilience is closely related to decision-making since maintenance (Attajer et al., 2019), production and quality engineering all contribute to achieve resilience, for example through predictive, prescriptive and adaptive approaches and knowledge-based systems (Nemeth et al., 2019). This paper particularly focuses on the evaluation and assessment of operational resilience, as a specific type of resilience related to the management of operations and continuity of production flows. The focus is specifically on single manufacturing plants rather than entire supply chains or production networks. A systematic literature review, following the methodology proposed by (Thomé et al., 2016), was carried out to identify the main works on the evaluation and assessment of operational resilience. This systematic review investigates research articles, and conference papers, the process followed for this literature analysis is described in **Error! Reference source not found.**

Identification: The systematic review is conducted through Scopus and Web of Science databases of research works indexed up to November 2021. Firstly, we define the scope of the search query by converging the following groups of keywords into the title, abstract, and keywords: (1) *resilien**; (2) *metric* OR indicator* OR evaluat* OR estimat* OR assess* OR measure* OR quantif* OR index*; (3) *manufacturing OR "production system" OR factory OR "industrial operation" OR "production operation" OR "production operations" OR "industrial operations" OR "industrial process" OR "production process"*; (4) *CPS OR CPPS OR CPMS OR cyber-physical**. The first group emphasizes resilience or resilient systems, the second limits the research for indicators and resilience evaluation, the third cluster restricts to manufacturing or production systems, and the

fourth cluster limits the research to CPPS. The scope of the research is limited to journal and conference articles, published in English. Therefore, the identification phase is concluded with 102 duplicated articles.

Screening: In this phase, each article is screened in the title, to eliminate duplicated articles, and in abstract and keywords to evaluate if it is adherent to the scope. Among 102 articles, 89 are excluded since they do not consider resilience in CPPS, or they do not study the resilience evaluation. 13 within the desired focus.

Eligibility: During this phase, the 13 retained articles are analyzed by reviewing the full texts and 5 were rejected as they do not meet the scope of the analysis.

Included: 8 articles are included for deeper analysis. 11 publications were included by the snowball process, totaling 19 analyzed works. These documents are reviewed thoroughly to identify the information relevant to the scope of this review.

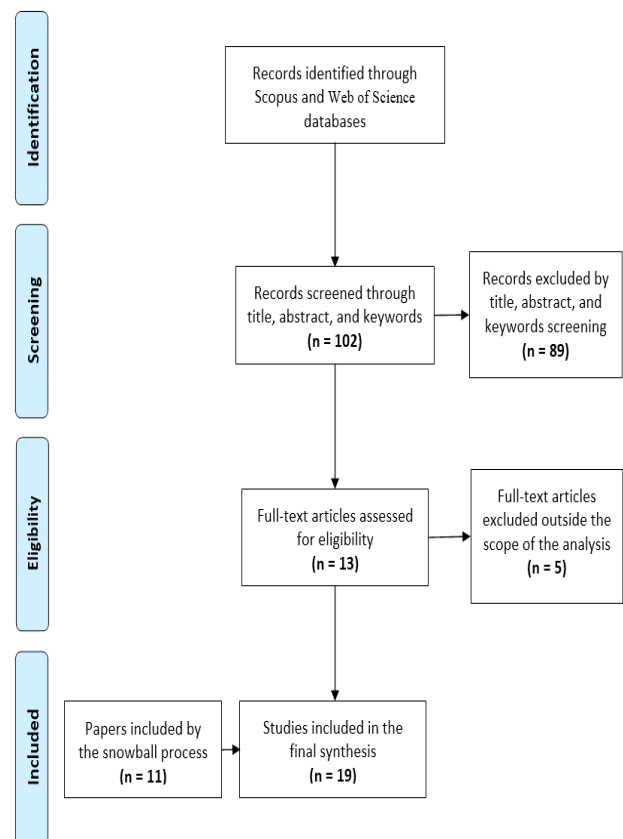


Fig. 1. Literature search methodology.

3 CONTENT ANALYSIS

This section reviews the relevant literature included in the section 2. The objective is to categorize the articles by focusing on the approach used to assess operational resilience, and the CPPS components for which resilience is assessed (*resilience of what?*). This concerns the manufacturing system, human factor, the Data/Information/Knowledge (DIK), or control mechanisms.

3.1 Performance indicators to measure operational resilience of manufacturing system

(Gu et al., 2015) define production loss, throughput settling time, and total underproduction time as three KPIs to measure operational resilience. They use defined KPIs to design a reconfigurable manufacturing system. The authors investigate different scenarios with respect to the system configuration, level of redundancy or flexibility, and buffer capacities. (Galaske and Anderl, 2016) propose a simulation-based decision support for the disturbance management process in a resilient cyber-physical production system. A set of scenarios for disturbed events are modeled and simulated. The simulation results for each scenario are evaluated using the following KPIs: throughput per hour, average throughput time, and the value-added rate. (Erol et al., 2010) use three KPIs to measure the resilience of a manufacturing system. This concerns level of recovery compared to the initial or disturbed levels, recovery time and level of vulnerability. (Potok et al., 2018) use throughput, latency end-to-end delay, and the load to assess resilience of manufacturing plant. (Zahoransky et al., 2015) use two KPIs to assess operational resilience. The first one concerns resource utilization rate and second one the roll-out process for finished product that defines at which extent the process output is used as an input for another process. (Gu et al., 2014) use throughput settling time with regards to the time needed from a manufacturing system to recover to its steady state and overtime to recover to offset production loss. (Guizzi et al., 2020) use throughput time, mean and standard deviation of cycle time (i.e., difference between production system output and input timestamps), and resource utilization to evaluate resilience of a manufacturing system. (Ribeiro et al., 2021) assess the overall equipment efficiency which identifies the percentage of manufacturing time that is truly productive. Finally, (Henry and Emmanuel Ramirez-Marquez, 2012) compute a delivery function that can be a network or flow after its recovery from disturbance.

3.2 Quantitative methods to measure operational resilience of manufacturing system

Other works have proposed mathematical models and quantitative approaches to measure operational resilience. (Caputo et al., 2019) suggest a quantitative method consisting of seven steps to compute the resilience in a single production plant. The authors use a time-dependent capacity function related to flow rate of production outputs and economic loss. However, the evaluation resilience in this paper is limited to manufacturing system, machines, and their related services. (Youn et al., 2011) propose three level approach to assess resilience in production system. The first level concerns allocation problem to incorporate the tradeoff decisions regarding reliability, efficiency, and component redundancy. The second level relies on reliability optimization to determine optimal component design while ensuring that target components are optimally allocated. The third level establishes

prognosis and health management to enable meeting the efficiency and reliability of the allocation for the first level. (Hu et al., 2013) suggest a mathematical model to measure resilience by minimizing costs of lost demand, production, and inventory storage in a production system. (Farid, 2015) assesses resilience of services of a flexible manufacturing system by using a graph theory and axiomatic design. The objective is to determine the existence and number of paths that can be used to provide a service. Operational resilience can be also assessed by artificial intelligence approaches. (Park et al., 2021) use reinforcement learning to enable adjustment of parameters by repeating episodes to learn the policy network. The reward function is designed to minimize the makespan and the standard deviation of cycle time.

3.3 Semi-qualitative methods to measure operational resilience of manufacturing system

Operational resilience is also assessed using semi-qualitative approaches. (McFarlane et al., 2018) propose a simple framework to assess the maturity of operational resilience in production control. The objective is to capture four identified dimensions that would be useful to ensure a reasonable degree of resilience for a particular operation. (1) “*awareness*” which refers to previous or future potential disturbances. (2) “*preparation*” is based on disturbances prediction. (3) “*management*” which refers to the decision-making to be taken to manage the disturbance and finally (4) “*response*” to determine which actions can be taken. Moreover, four levels are defined to support each of the dimensions. A given dimension is said to be of level 0 if little or no direct appreciation of disturbances within the day-to-day operations is being noted. Level 1 refers to a general appreciation of the potential disturbances while level 2 represents a detailed quantitative understanding of disturbances. Finally, level 3 refers to real time learning based approach for improving resilience. (Stolker et al., 2008) use a multi attributed utility theory to design a value tree of operational resilience and thus obtain a score of the company’s resilience management performance. The scores obtained from all the performance measures at the bottom of the value tree and the weights assigned to attributes and objectives to determine the overall score of resilience.

3.4 Operational resilience from Data, Information, Knowledge (DIK) perspective

The data and information are fundamental features to ensure the resilience in the context of CPPS. (Bagozi et al., 2021) used a data driven approach to assess the relevance of data and the resilience of the control mechanism. Four features are used for this purpose:

- processing time required to promptly detect anomalies and activate recovery services,
- quality of data used to support identification of anomalous conditions,

- data summarization and relevance of evaluation techniques to detect anomalies efficiently and promptly on the monitored system and the availability of dashboards to display suggested recovered services,
- average response time to apply data summarization.

3.5 Operational resilience from control mechanism perspective

The control and decision-making mechanisms are fundamental features to ensure the operational resilience in CPPS.

(Moghaddam and Deshmukh, 2019b) investigate the assessment of the resilience of control mechanism with regards to two types of disturbances: non-cascade disturbances and cascade disturbances, which refers to a process in a system of interconnected parts in which the failure of one or few parts can trigger the failure of other parts and so on. The authors consider a network representation of manufacturing control structures as directed and weighted graphs in which vertices and edges respectively denote the control units and the relationship between them. Thus, the relative weights of hierarchical and heterarchical edges determine the position of a control structure on the hierarchy-heterarchy spectrum.

3.6 Operational resilience from a human factor perspective

Another dimension of operational resilience in CPPS is the human factor. (Azadeh et al., 2014) suggest a human-centered framework to assess the performance of safety and human resources by considering 10 dimensions. (1) Top-level management recognizes the concerns and problems of the human performance and safety and tries to solve them. (2) Reporting culture supports the reporting of problems and issues up through the organization or system, yet not tolerating culpable behaviors. (3) Learning emphasizes the analysis of normal work while it does not ignore learning from accidents, incidents, and other events. (4) Awareness understands the quality of human performance and status of defenses in the system by data gathering. (5) Preparedness allows organization or system actively anticipates the problems of human performance inhuman-machine systems and prepares to cope with them. (6) Flexibility enables the system or organization to adapt the complex or new problems so that it maximizes the ability of the system to solve the problems without disturbing overall functionality. (7) Self-organization provides multiple independent entities with a knowledge limited to their environment that are locally interacted (directly or indirectly) to generate a result. (8) Teamwork offers greater adaptability and productivity better than anyone an individual might offer while raising job satisfaction and staff maintenance. (9) Redundancy defines the absence of critical components whose failure would cause collapse of the structure and

existence of alternative pathways from the sources to demand or surplus capacity in normal conditions, for use when components become unavailable. And finally, (10) Fault-tolerant maintains the specified performance of a system in the presence of errors.

4 SYNTHESIS AND DISCUSSION

Literature review based on selected papers shows different approaches based on: KPIs, quantitative methods, semi-qualitative methods, knowledge-based approach, data-driven approach, and human-centered approach. Every paper focuses on specific component to define “the resilience for what?”: human factor, Data-Information Knowledge (DIK), control mechanism, and manufacturing systems. The Tab. 1 synthesizes the interconnection between the approaches and the components in terms of number of papers.

Tab. 1. Interconnections between “approaches” and “the resilience for what?”.

		Resilience of What?				Total
		human factor	DIK	control mechanism	manufacturing system	
Approaches	KPIs				41%	41%
	Quantitative methods			5%	22%	27%
	Semi-Quantitative methods		5%	5%	10%	20%
	Data-driven approach		5%	5%		10%
	Human-centred approach	5%				5%
Total		5%	10%	15%	73%	

As shown in the Tab. 1, most of the papers (41%) are interested on proposing KPIs to assess the operational resilience of manufacturing systems. They tend to define the KPIs necessary to evaluate the resilience such as the rate of production and the average cycle time of the system. 27% of the studied works use “Quantitative methods” to evaluate resilience of manufacturing systems such as the sum of equipment reconstruction cost, business interruption and material loss. The analysis of the literature also highlighted that most papers (about 73% of the studied papers) evaluate the resilience at the level of the manufacturing plant and do not cover all components of CPPS. “DIK” and “control mechanism” issues are almost studied in the same way than the proposed approaches. “Human factor” is the least studied in the literature regarding the other CPPS components.

According to these results, new approaches are needed to be explored that ensure tradeoffs among all components of CPPS. These approaches should further assess the relationship between the resilience of the built environment (e.g., products, resources, manufacturing process), human factor, DIK-driven standards, and control mechanisms. As CPPS components are by nature interconnected and thus vulnerable to disturbances, an efficient approach for assessing the operational resilience should integrate all the components.

One of the important challenges of disturbances management in CPPS is to make sense of the levels and dimensions that can support a developmental pathway for improving operational resilience. One paper (McFarlane et al., 2018) considers the different dimensions to ensure a reasonable degree of operational resilience in CPPS. In addition, these dimensions reflect the chronological steps related to disturbances management. The awareness and preparedness represent the actions before the disturbance occurrence. The management and response represent the actions during and after the disturbance occurrence.

5 CONCLUSION AND PERSPECTIVES

A systematic literature review is undertaken to identify the KPIs and approaches to assess the operational resilience of CPPS. Furthermore, a review analysis is presented to reveal challenges of evaluation of operational resilience in the CPPS. The analysis is categorized to consider either KPIs, quantitative methods, semi-qualitative methods, knowledge-based, data-driven, and human-centered approaches used to assess the operational resilience. It highlighted that “human-centered” approaches are less studied in the presented papers. Also, most papers consider only the assessment of resilience at the level of the manufacturing plant and do not cover all CPPS components. As CPPS objects are interconnected and thus vulnerable to disturbance, an efficient approach for assessing their resilience should integrate all its components. Another challenge is articulating levels and dimensions which can support an operational resilience improvement in CPPS. The resilience dimensions must reflect the chronological steps associated with disturbances management: before, during, and after the occurrence of disturbances.

As for perspectives, we aim to address the identified gaps by developing a framework for evaluation of operational resilience in CPPS. Two major features will be identified. The first one is related to the levels and dimensions to ensure a reasonable degree of operational resilience. The second feature is linked to the CPPS components to cover the resilience of all the CPPS components. Therefore, this framework can provide valuable insights and support to decision makers in the planning of mature resilience strategies in CPPS.

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