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Life cycle and metrics to measure the resilience of business processes by considering resources

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Abstract

Purpose – Enterprises often face a wide variety of adverse events. Adverse events can have negative effects on organizations like failures of resources. In case resources fail, they are not available and cannot perform the assigned work. Enterprises are therefore especially interested in how resilient processes and workflows are in case adverse events occur and resources may fail. For this purpose, process resilience measurement approaches are needed.

Design/methodology/approach – To measure the resilience of processes and workflows, a life cycle and five quantitative metrics have been developed. The metrics have been validated using five real-world production and logistics cases to show their applicability on process models and paths. Furthermore, workshops have been conducted with professionals to get additional feedback on the contributions.

Findings – Based on the results obtained from applying the metrics to five real-world cases, view-based resilience improvements can be derived. Overall, only one of the five real-world cases can be considered as completely resilient. Furthermore, the metrics and life cycle have been especially valued by professionals with respect to transparency, independency, comparability as well as the ability to determine critical process paths.

Originality/value – Several authors have dealt with different aspects related to the measurement of business processes, resilience or a combination thereof. However, a life cycle or metrics to quantitatively measure the resilience of processes by considering resources has not been found yet. The life cycle and metrics are therefore novel. As a future research direction, they can be applied in different domains for further validation purposes.

Keywords Business process management, Measurement, Metrics, Resilience, Resource, Redundancy

Paper type Research paper

1. Introduction

Enterprises often face a wide variety of adverse events during their existence. Adverse events can negatively affect human or machine resources, with impacts on enterprise operations. Disruptions of globally connected supply chains (Paul and Chowdhury, 2020) and the unplanned nonavailability of mission-critical resources (Snedaker and Rima, 2014) are two examples of impacts companies may deal with.

In case resources are not available as planned, business processes cannot be performed. As a result, outputs like products or services of business processes may not be timely produced or delivered to customers. Consequently, customers can lose trust in the ability of an enterprise to supply goods and services as ordered and finally may decide to buy them from one of the competitors. This can significantly reduce revenues and in the long-term threaten the existence of the company.

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Knowing this, dealing with adverse events and negative impacts on enterprise resources can be crucial for the success of any company. The concept of resilience holds promise to find answers to deal with adverse events and their impacts. It encompasses the ability to prepare, prevent, protect, respond and recover from adversity (Thoma *et al.*, 2016). In this regard, the concept of resilience can feature several attributes like robustness (Furuta, 2015), adaptability (Linnenluecke, 2017), flexibility or redundancy (Sheffi and Rice, 2005). This paper especially considers redundancy as an attribute of resilience with the aim to continue processes by replacing resources. In this context, the following research questions are addressed:

(1) How can the concept of resilience be combined with business process management?

(2) How resilient are process models and paths in case resources fail?

(3) How valuable is the research conducted to measure the resilience of processes?

To answer the first question, a life cycle with five different views has been developed integrating the perspective of resilience into business process management (BPM) life cycle phases. The life cycle should serve analysts as a basis to holistically analyze resilience issues throughout different process and workflow stages.

To answer the second question, five quantitative metrics to measure the resilience of processes are provided. The metrics show the degree of resilience workflows and processes possess from different angles. They can be used, for example, to determine prioritizations to improve the resilience of processes and workflows.

The last question is addressed in two different ways. The applicability of the metrics and related resilience findings is demonstrated using one real-world manufacturing case and five production and logistics cases. Furthermore, workshops have been conducted with professionals to get feedback about the added value and possible improvements of the contributions proposed.

The remainder of this paper is structured as follows. Section 2 states related work. Section 3 outlines the basics for all subsequent sections. Section 4 explains the life cycle and metrics proposed. Section 5 validates the life cycle and metrics. Section 6 describes managerial implications. Section 7 provides a summary of the work proposed.

2. Related work

In this section, research work regarding life cycle measurement concepts and metrics considering business processes as well as resilience that relate to some extent to the approach proposed in this paper is introduced.

Generally speaking, several authors have dealt with different aspects related to the measurement of business processes or resilience or a combination thereof. However, to the best of the authors' knowledge, metrics to quantitatively measure the resilience of process models and paths by considering resources have not been found at the time of submitting this work.

The work of Zahoransky *et al.* (2015) contributed a decision support framework to combine the measurement of resilience in a BPM context. The authors present the components of the framework, which aim to detect resilience properties by analyzing log-files. The work deals with the resilience of processes by considering a post-execution view, while the work in this paper is mainly based on a pre-execution view. The authors also stated that there is no suitable holistic measurement system for resilient BPM in place by now. One contribution to close this gap is the process resilience life cycle proposed in section 4.1 of this paper.

The research papers of Allen and Davis (2010), Caralli *et al.* (2010), Allen (2011) and Allen and Curtis (2011) are related work of mainly the same authorship that deals with the question of how operational resilience can be measured. The authors define high-level objectives for managing operational resilience and demonstrate how meaningful metrics can be derived from these objectives. In contrast to this high-level and conceptual work, this paper provides quantitative metrics for operational resilience management purposes.

Mendling (2008) presents, besides an overview of existing metrics, several other metrics that capture various aspects related to the process model structure or the process model state space. These metrics are discussed with their impact on error probability. Errors and failures of process models are also part of resilience considerations. However, this paper deals with resilience matters by considering the resource perspective, which is not captured by the related work mentioned.

Bhuiyan *et al.* (2007) provide some metrics related to actor criticality and vulnerability. The authors state that they believe the metrics can help analysts to delegate dependencies among various actors, choose alternatives, decompose tasks, maintain consistency among organizational and process models or handle exceptions. The metrics are applied by use of organizational models. In contrast to this related work, the metrics in this paper are measured by use of business process models and paths.

Lee *et al.* (2019) propose an approach to identify suitable substitutes in case initially assigned human resources are unavailable. The approach uses process mining and social network analysis to derive a metric called degree of substitution, which measures how much the work experiences of human resources overlap by considering two perspectives: task execution and transfer of work. It uses event logs for respective analyses. Therefore, the analyses of the related work are based on a post-execution view, while the work in this paper is mainly based on a pre-execution measurement view.

Further metrics and measurement concepts exist that make use of, for example, workflow nets, business processes and graphs to evaluate various attributes like complexity (Gruhn and Laue, 2006; Cardoso *et al.*, 2006), quality (Vanderfeesten *et al.*, 2007) or performance (van Looy and Shafagatova, 2016). They have some similarities although they using other terms and are not clearly delineated from each other.

Sahebjamnia *et al.* (2018) provide an integrated business continuity and disaster recovery planning model with the aim to respond to disruptive incidents appropriately. The model considers both internal and external resources that can be required for a variety of measures such as the execution of continuity plans. The model demonstrates the interaction between organizational resilience and required resources but does not consider the perspective of processes and workflows as the work in this paper aims for.

Sanchis *et al.* (2020) propose a resilience-related conceptual reference framework. The framework considers disruptive events as well as preparedness and recovery capabilities that support situational transition using preventive and knowledge registration action. It indicates knowledge registration related to the occurrence of disruptive events and recovery actions to be performed to restore regular enterprise operation levels. The framework touches several aspects that can also be linked to the knowledge of resources. However, it does not consider a life cycle-based view of processes and workflows as this paper intends.

Duchek (2020) proposes a meta-capability conceptualization with regard to resilience. The work introduces resilience stages with underlying capabilities that can be used to cope with unexpected events and to bounce back from crises. The capabilities as a whole are considered to form organizational resilience. They are associated with knowledge base, resource availability, social resources as well as power and responsibility as antecedents and drivers. The work addresses resource availability as one important factor for organizational resilience. However, this paper primarily considers resource redundancy as an additional feature to foster resilience.

Extensive literature reviews with regard to resilience also covering, for example, resource as well as crisis aspects are provided by Linnenluecke (2017), Fraccascia *et al.* (2018), Ruiz-Martin *et al.* (2018) and Hillmann and Guenther (2021). These literature reviews cover a wide variety of work with regard to organizational resilience and can be used for scoping purposes considering the quite diverse subject area of resilience.

3. Basics

3.1 Business process management

BPM generally deals with aspects related to the design, configuration, enactment as well as evaluation of workflows and processes (Weske, 2012). Process models are usually flow abstractions of some (socio-technical) system to be considered in whole or in part. A process model consists of one or more (branching) process paths. A branching process path can, for example, be represented by split constructs. Process paths represent the paths to be executed (simultaneously) at runtime (Ougaabal *et al.*, 2020). One execution of a process path is called a process instance (Russell *et al.*, 2005).

Independent from any modeling notation, workflow and process models consist of nodes and edges (Weske, 2012). In BPMN, nodes refer to specific notation elements like activities, gateways or events (Dumas *et al.*, 2018). Edges are mainly used to express the control-flow by connecting nodes. Resource nodes, as defined in this paper, are nodes that need resources for execution like activities or tasks in BPMN. Furthermore, resource-redundant nodes are nodes for which one or more resources are available as replacements in case assignable resources fail at a particular time.

3.2 Resources

Resources refer to anyone or anything involved in the execution of workflows and processes (Dumas *et al.*, 2018). They are used and systematized quite differently in scientific literature depending on the context they are used. Russell *et al.* (2016) distinguish between human (e.g. worker) and nonhuman (e.g. equipment or plant). Dumas *et al.* (2018) differentiate between active resources which can autonomously perform activities, and passive resources that may be used by active resources to achieve the defined output of activities.

In this paper we focus on exclusive resources as described by Winkler *et al.* (2012). These resources are exclusively assignable to a resource node like an activity for a certain period to perform the work defined. Exclusive resources are humans, application systems or manufacturing machines and can be subsumed as human and machine resources (Ferstl and Sinz, 1998). They are sometimes also called "private" as they are not accessible and shareable by different activities at the same time (Li *et al.*, 2004). Exclusive resources can, as a rule, also be replaced by other resources in case of failure.

3.3 Resilience

The failure of resources caused by adverse events is a main topic discussed within resilience literature (Hillmann and Guenther, 2021; Vogus and Sutcliffe, 2007). It is embedded in the view of resilience as a holistic concept with exemplary phases to prepare, prevent, protect, respond and recover from adversity (Thoma *et al.*, 2016). Although the concept is still in its infancy (Duchek, 2020) with different definitions used across research disciplines (Birkie *et al.*, 2013), it generally refers to events which have negative effects on system operations (Erol *et al.*, 2009).

In case system operations have been affected by adverse events, they can be considered as vulnerable. Based on this point of view, vulnerability can be understood as the opposite of resilience (Erol *et al.*, 2010). Reducing vulnerability is thus accompanied by an increase of resilience (Sheffi and Rice, 2005). As adverse events can also affect vulnerable business processes and workflows, the concept of resilience is undoubtedly of interest from a BPM perspective.

Due to its holistic nature, the concept of resilience features also various attributes (Ruiz-Martin *et al.*, 2018). One main attribute within the context of resilience is redundancy (Fraccascia *et al.*, 2018; Sheffi and Rice, 2005), which is of main interest in this paper. Redundancy refers to the extent that specific systems, system elements or other units are substitutable (Tierney and Bruneau, 2007). It is the ability of certain system components to assume the functions of failed components without adversely affecting the performance of the system itself (Haimes, 2009).

4. Process resilience life cycle and metrics

4.1 Process resilience life cycle

In this section, a life cycle is proposed to combine the concept of resilience with BPM. The life cycle aims to systematically detect resilience analysis possibilities by considering different stages of business processes and workflows. The life cycle was developed based on existing BPM life cycle constructs (Weske, 2012). It is depicted in Figure 1. The different phases of the life cycle are explained below.

4.1.1 Resilience by design. The first phase of the process resilience life cycle is called *resilience by design*. This phase analyzes structural aspects of workflow and process diagrams with regard to resilience. Structural aspects are related to modeling elements which, in turn, depend on the notation used or possible extensions thereof. Depending on the expressiveness of the notation used, different perspectives can be considered for resilience analysis such as resources, data or inputs. This phase answers the question of how resilient workflows and processes are designed.

4.1.2 Resilience by implementation. Resilience by implementation is the second phase of the process resilience life cycle. This phase deals with techniques to be applied during the implementation of processes and workflows such as backup or testing concepts. The scope ranges from preventive to reactive measures, that is, they can be invoked before, during and after

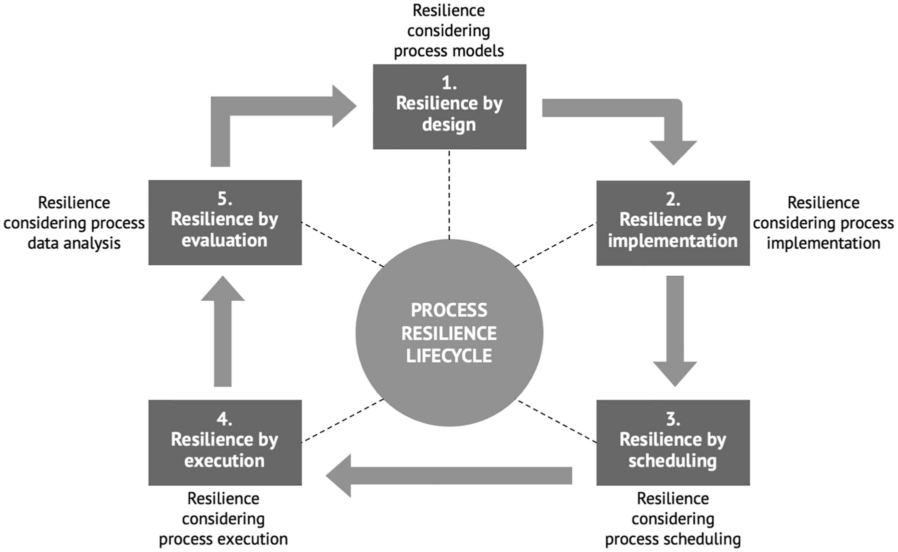

Figure 1.
Process resilience life cycle phases partly based on Weske (2012)

disturbances. *Resilience by implementation* therefore aims to build, monitor and detect resilience functionalities. It answers the question of how resilient processes and workflows are realized to absorb disturbances.

4.1.3 Resilience by scheduling. The third phase of the process resilience framework is called *resilience by scheduling*. This phase relates to the resilient planning of process executions. A resilient planning of process executions generally depends on the risk appetite to be taken by decision-makers and are related to different criteria such as availabilities and assignment possibilities. As the planning of process executions can be subject to change, associated resilience values may also change. *Resilience by scheduling* therefore answers the question of how resilient process executions are scheduled considering a particular time.

4.1.4 Resilience by execution. Resilience by execution deals with runtime issues of process executions. Runtime issues are errors, interruptions or failures occurring during process executions and may prevent process instances to proceed for a certain period. They may need specific mechanisms to be applied in order to continue operations properly. The aim of *resilience by execution* is to handle exceptional behaviors of process instances. This phase therefore considers the question of how resilient process instances are in case exceptional behavior like disturbances occur.

4.1.5 Resilience by evaluation. Resilience by evaluation is the last phase of the process resilience life cycle and considers the data created by process instances. It is a retrospective view and is based on the analysis of log files created by process instances. One objective of this phase is to uncover and propose improvements based on historic data of process instances with regard to resilience issues such as failures. *Resilience by evaluation* is therefore associated with the question of how resilient process instances actually had been. The results of this phase can also be used for possible adjustments to strengthen the resilience of processes in the future.

The process resilience life cycle typically starts by the design (phase 1) of models and ends by the evaluation (phase 5) using data generated by process instances. However, the analysis of workflows and processes with regard to resilience may begin with any of the phases comprising the process resilience life cycle. It depends on the current state as well as on the preferences of process and workflow analysis. Furthermore, different phases of the process resilience life cycle are to some extent related. For example, if process and workflow executions are resiliently scheduled (*resilience by scheduling*), the probability that failures and errors can be compensated at runtime (*resilience by execution*) may increase.

4.2 Process resilience metrics

In this section, five metrics related to the resilience of business processes are proposed. The metrics can be used as indicators to measure the degree of resilience or vulnerability (as opposite of resilience) business processes possess. They are described with their respective definition, result and explanation below.

4.2.1 Human Intensity. 4.2.1.1 Definition. The metric *human intensity* (*HI*) depicted in equation (1) specifies how a process path depends on human resources. The numerator counts all nodes of a process path which require humans for execution ($|HN|$). The denominator counts all resource nodes of a process path ($|RN|$). Resource nodes are nodes that require resources (e.g. humans or nonhumans) for execution. Examples of resource nodes are activities or tasks in BPMN. The metric can be calculated for one or more process paths of a process model. In case the metric is calculated for a process model, the respective nodes need to be counted for all process paths of the process model.

$$HI = \frac{|HN|}{|RN|} \, with \, 0 \leq HI \leq 1 \tag{1}$$

4.2.1.2 Result. The result of the metric ranges from $0 \leq HI \leq 1$. $HI = 1$ means that all nodes of a process path are associated with humans; $0 < HI < 1$ means that some (but not all) nodes of a process path are associated with humans; and $HI = 0$ means that no node of a process path is associated with humans. In this case, a process path is fully automated.

4.2.1.3 Explanation. The metric shows the relative degree one process path depends on humans. The higher this degree, the more humans are needed to execute a process path in relative terms. If more humans are needed to execute one process path, human-related vulnerabilities may be higher.

4.2.2 Machine Intensity. 4.2.2.1 Definition. The metric *machine intensity* (*MI*) depicted in equation (2) specifies how a process path depends on machine resources. The numerator counts all nodes of a process path which require machines for execution ($|MN|$). The denominator counts all resource nodes of a process path ($|RN|$). The metric can be calculated for one or more process paths of a process model. In case the metric is calculated for a process model, the respective nodes need to be counted for all process paths of the process model.

$$MI = \frac{|MN|}{|RN|} \, with \, 0 \leq MI \leq 1 \tag{2}$$

4.2.2.2 Result. The result of the metric ranges from $0 \leq MI \leq 1$. $MI = 1$ means that all nodes of a process path are associated with machines; $0 < MI < 1$ means that some (but not all) nodes of a process path are associated with machines; and $MI = 0$ means that all nodes of a process path have no associated machines. In this case, a process path is manually executed.

4.2.2.3 Explanation. The metric shows the relative degree one process path depends on machines. The higher this degree, the more machines are needed to execute a process path in relative terms. If more machines are needed to execute a process path, machine-related vulnerabilities may be higher.

4.2.3 Model Redundancy Degree. 4.2.3.1 Definition. The metric *model redundancy degree* (*MRD*) depicted in equation (3) specifies the resource redundancy degree of a process model by considering the resource redundancy of its paths. The numerator counts all completely resource-redundant paths ($|RRP|$) of a process model. A completely resource-redundant path consists of resource nodes, which all have redundant resources for replacement. The denominator counts all paths of a process model ($|P|$).

The (resource-redundant) paths of a process model can, for example, be counted using existing or enhanced functionalities of BPM systems. BPM systems are usually able to coordinate process instances along process model paths and may also integrate resource information. The numerator and denominator values of the metric can be determined based on this information. Thus, the metric results can subsequently be calculated using such kind of systems.

$$MRD = \frac{|RRP|}{|P|} \, with \, 0 \leq MRD \leq 1 \tag{3}$$

4.2.3.2 Result. The result of the metric ranges from $0 \leq MRD \leq 1$. $MRD = 1$ means that a process model is completely resource-redundant; $0 < MRD < 1$ means that some (but not all) paths of a process model are completely resource-redundant; and $MRD = 0$ means that no path of a process model is completely resource-redundant.

4.2.3.3 Explanation. The metric shows the relative resource redundancy degree of a process model by considering the resource redundancy of its paths. The higher this degree, the more paths of a process model are fully resource-redundant. A fully resource-redundant process model can be considered as resilient as it can replace every resource at least once.

4.2.4 Resource redundancy degree. 4.2.4.1 Definition. The metric *resource redundancy degree* (*RRD*) depicted in equation (4) specifies the resource redundancy degree of a process path. It answers the question of how much a process path is resource-redundant. The numerator counts all resource-redundant nodes of a process path ($|RRN|$). Resource-redundant nodes are nodes for which one or more resources are available as replacements in case resources fail. The denominator counts the amount of resource nodes of a process path ($|RN|$). The metric can be calculated for one or more process paths of a process model. In case the metric is calculated for a process model, the respective nodes need to be counted for all process paths of the process model.

$$RRD = \frac{|RRN|}{|RN|} \, with \, 0 \, \leq \, RRD \, \leq 1 \tag{4}$$

4.2.4.2 Result. The result of the metric ranges from $0 \leq RRD \leq 1$. $RRD = 1$ means that a process path is completely resource-redundant, that is, every resource associated with a process path has at least one resource for replacement; $0 < RRD < 1$ means that a process path is partly resource-redundant as some (but not all) resources associated with a process path are redundantly available; and $RRD = 0$ means that a process path is not resource-redundant at all as no resource associated with a process path is redundantly given.

4.2.4.3 Explanation. The metric shows the relative resource redundancy degree of a process path. The higher this degree, the more resources associated with a process path can be replaced at least once in relative terms. In case every resource associated with a process path can be replaced at least once, this process path can be considered as resilient.

4.2.5 Resource redundancy intensity. 4.2.5.1 Definition. The metric *resource redundancy intensity* (*RRI*) depicted in equation (5) specifies the resource redundancy intensity of a process path. It shows the average resource redundancy level of a completely resource-redundant process path. The numerator counts the number of redundant resources associated with a process path ($|RRA|$). The denominator counts the number of resource nodes of a process path ($|RN|$). The variable *resource redundancy* (*RR*) is of value 1 if every resource associated with a process path has at least one resource as replacement, otherwise 0. The metric can be calculated for one or more process paths of a process model. In case the metric is calculated for a process model, the respective amounts need to be counted for all process paths of the process model.

$$RRI = \frac{|RRA|}{|RN|} * RR \, with \, 0 \, = \, RRI \, \geq 1 \tag{5}$$

4.2.5.2 Result. The result of the metric ranges from $0 = RRI \geq 1$. $RRI = 0$ means that not all resources associated with a process path are redundantly available. $RRI = 1$ means that for each resource associated with a process path, exactly one redundant resource exists. $RRI > 1$ means that every resource of a process path is redundantly available with one or more resources are multiply redundant.

4.2.5.3 Explanation. The metric shows the relative resource redundancy intensity of a process path. The higher the value of the metric, the more resources of a process path can on average be replaced in relative terms. The more resources related to a process path are replaceable, the more this process path can be considered as resilient.

4.3 Process resilience metric applicability

In this section the applicability of the metrics proposed in section 4.2 to process models and paths as well as to each process resilience life cycle phase proposed in section 4.1 is explained. For each life cycle phase it is stated whether and under what conditions the metrics can be applied. An overview of the metrics applicability is depicted in Table 1 and described below.

Each metric is applicable to process models and paths with exception of the metric *model redundancy degree*. This metric can only be calculated for process models as it needs the redundancy status of each process model path as input.

Table 1.
Metric applicability overview

Metric	Process path	Process model	Resilience by design	Resilience by implementation	Resilience by scheduling	Resilience by execution	Resilience by evaluation
Model redundancy degree	–	X	(X)	(X)	X	X	(X)
Human intensity	X	X	(X)	(X)	X	X	(X)
Machine intensity	X	X	(X)	(X)	X	X	(X)
Resource redundancy degree	X	X	(X)	(X)	X	X	(X)
Resource redundancy intensity	X	X	(X)	(X)	X	X	(X)

Note(s): x = applicable; (x) = conditionally applicable; – = not applicable

The result of the metrics can be calculated using the design of process models (*resilience by design*) if certain conditions are met. In case process models have been designed in such a way that all resources required for executions can be determined, the metrics can be calculated. However, this is usually not the case as process models are design abstractions (Salnitri *et al.*, 2017) of some real-world system flows. As such, they often do not contain all resource information for their execution flows.

For example, BPMN provides pools and lanes as two constructs to model resource aspects (Dumas *et al.*, 2018). These constructs are regularly too coarse-grained for modeling detailed resource information. For instance, a user task represents an atomic level of work in BPMN to be performed by a human with assistance of a software system (Object Management Group, 2013). It can be placed in one pool or lane. However, a pool or lane is either labeled for referring to a human or machine entity, but not both. This means that only one of the two resources can be determined by the design of process models.

The result of the metrics can also be calculated for the phases *resilience by scheduling* and *resilience by execution*. Information about assignable resources has to be available as soon as process executions are going to be scheduled (*resilience by scheduling*). Otherwise, this and subsequent phases cannot begin. The results of the metrics can be subject to change at any time during the phases *resilience by scheduling* and *resilience by execution*. They depend on the current resource availability and demand for (possibly concurrent) process scheduling and execution. A change in either of these variables may result in a change of the respective metric values.

The result of the metrics can also be calculated in case log files contain all necessary resource data and states of already performed (parts of) process paths (*resilience by evaluation*). Usually, some information like data about redundant resources is not contained in log files. However, this information must be available as a prerequisite to calculate metrics related to resource redundancy on a post-execution basis.

5. Validation

5.1 Manufacturing case

In this section, the metrics introduced in section 4.2 are applied to a manufacturing case consisting of a real-world manufacturing process model and a resource model. The case is mainly used to show the applicability of the metrics to process paths with related findings derivable. It was provided by an industrial company. Some information (like the company name or the activity names of the manufacturing process model) cannot be disclosed for reasons of confidentiality.

5.1.1 Manufacturing process model. The manufacturing process model is depicted in Figure 2. It captures the manufacturing of different variants of carbide products and was modeled using BPMN. The model consists of 17 nodes (letters A to Q above each node) which are activities or gateways. Eleven of these are resource nodes (A,C,E,F,G,H,K,L,N,O,P) which represent tasks of different kinds. For each resource node, the type of resource required for execution has been determined. Semi-automated resource nodes like BPMN user tasks have been further divided into atomic human or machine nodes for analysis purposes. Consequently, the resource nodes are either performed manually by a human like an employee (depicted as human pictogram) or automatically by a machine like a manufacturing or application system (depicted as machine pictogram).

5.1.2 Resource model. The resource model is depicted in Table 2. It contains some resource data related to the manufacturing process model. *Assignable resources* specify the number of resources to be allocatable for the execution of respective resource nodes. For instance, 4 humans are available for assignment and execution of resource node A. *Redundant resources* are the number of resources to be available for replacements in case initially assigned resources fail (*assignable resources* - 1). For instance, if one assigned machine to resource node C fails, another machine is available for replacement.

5.1.3 Results and findings. The results obtained from applying the metrics to the manufacturing case are depicted in Table 3. The findings are explained below.

As a calculation example, the result of the metric HI for process path 1 (nodes: A-B-C-D-E-F-G-I-J-K) is obtained by dividing the amount of human nodes (A-E-G-K: 4) by the amount of resource nodes (A-C-E-F-G-K: 6), resulting in a metric value of 0,67. The result of the metric MI is calculated in the same way for process path 1 by considering machine nodes. To calculate the metric results for the process model, the same procedure is used considering all paths of the process model. Therefore, the result of the metric HI for the process model is obtained by dividing the amount of human nodes for all paths of the process model (38) by the amount of resource nodes for all paths of the process model (75) resulting in a metric value of 0.51. The

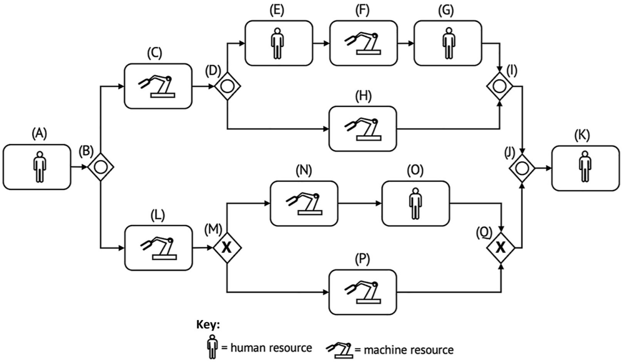

Figure 2. Manufacturing process model

Resource node	A	C	E	F	G	H	K	L	N	O	P
Assignable resources	4	2	3	3	5	2	5	2	1	4	2
Redundant resources (= assignable resources – 1)	3	1	2	2	4	1	4	1	0	3	1

Table 2. Resource model

Table 3.
Manufacturing case results

Process resilience metric	Human Intensity (HI)	Machine Intensity (MI)	Model Redundancy Degree (MRD)	Resource Redundancy Degree (RRD)	Resource Redundancy Intensity (RRI)
Process model	0.51	0.49	0.64	0.95	0.00
Process path 1 (nodes: A-B-C-D-E-F-G-I-J-K)	0.67	0.33	–	1.00	2.67
Process path 2 (nodes: A-B-C-D-H-I-J-K)	0.50	0.50	–	1.00	2.25
Process path 3 (nodes: A-B-C-D-E-F-G-H-I-J-K)	0.57	0.43	–	1.00	2.43
Process path 4 (nodes: A-B-C-D-E-F-G-I-J-K-L-M-N-O-Q)	0.56	0.44	–	0.89	0.00
Process path 5 (nodes: A-B-C-D-E-F-G-I-J-K-L-M-P-Q)	0.50	0.50	–	1.00	2.25
Process path 6 (nodes: A-B-C-D-H-I-J-K-L-M-N-O-Q)	0.43	0.57	–	0.86	0.00
Process path 7 (nodes: A-B-C-D-H-I-J-K-L-M-P-Q)	0.33	0.67	–	1.00	1.83
Process path 8 (nodes: A-B-C-D-E-F-G-H-I-J-K-L-M-N-O-Q)	0.50	0.50	–	0.90	0.00
Process path 9 (nodes: A-B-C-D-E-F-G-H-I-J-K-L-M-P-Q)	0.44	0.56	–	1.00	2.11
Process path 10 (nodes: A-B-J-K-L-M-N-O-Q)	0.60	0.40	–	0.80	0.00
Process path 11 (nodes: A-B-J-K-L-M-P-Q)	0.50	0.50	–	1.00	2.25

results of the metrics HI and MI add up to 1 for each process model and path as they show the shares of resource nodes either supported by human or machine resources.

The results show that process path 1 depends the most on human work (highest HI value of all process paths) in relative terms. In case adverse human-affecting events like diseases occur, this process path can be considered as most vulnerable for human-related failures. In contrast, process path 7 depends the most on machine work (highest MI value of all process paths) in relative terms. In case adverse machine-affecting events like power outages occur, this process path can be considered as most vulnerable for machine-related failures. By considering the linked view between adverse events and resources, these process paths can be considered as the most vulnerable ones in relative terms.

The process model is predominantly resource-redundant. This finding is based on the result that 64% of all process model paths are fully resource-redundant (MRD value of 0.64). For each resource node of these paths, a non-working resource can be replaced at least once by a working resource. Thus, these paths can be considered as resilient to a certain extent. However, some paths of the process model are not fully resource-redundant. They can be considered as vulnerable and prone to be disrupted as some of their associated resources cannot be replaced at all in case of failures. These process paths can be considered as resource redundancy bottlenecks of operations and are thus of first priority to be improved for resilience purposes.

The vast majority of resources associated with the process model can be replaced at least once. This finding is based on the result that 95% of resources can be replaced at least once if all resource nodes of every process path are considered (RRD value of 0.95). Process path 10 is the most vulnerable path with regard to resource redundancy in relative terms (lowest RRD value of all paths). This path is of first priority for resilience improvements in terms of resource redundancy followed by the paths 6,4,8 in that order. These process paths have in common that they depend on at least one resource which is not redundantly available.

Process paths 7,9,2-5-11,3,1 are of second priority for resource redundancy improvements in the partly equal order specified. These paths have in common that they depend on resources which are at least replaceable once with one or more resources are multiply replaceable. Process path 7 is the most vulnerable path by considering this group of paths, as it has, in relative terms, the least resources for replacements on average (with an RRI value of 1.83). On the contrary, process path 1 has, relatively speaking, the most resources for replacements on average (with an RRI value of 2.67).

5.2 Production and logistics cases

In this section, the metrics introduced in section 4.2 are applied to five production and logistics cases (four additional cases and the one explained in section 5.1). The cases are referred to as production cases hereinafter for reasons of simplicity. Each production case consists of a real-world process model (Figure 3) and a related resource model (Table 4). The production cases are used to show the applicability of the metrics to process models (Table 5) and related findings derivable. They were also provided by an industrial company, with some information not to be disclosed for reasons of confidentiality.

The results show that process model 2 depends, in relative terms, the most on humans (highest HI value of all process models) followed by process models 4,1-5,3 in that partly equal order. This order can be used as a prioritization if the aim is to prevent against impacts of events affecting humans. In contrast, process model 3 depends, relatively speaking, the most on machines (highest MI value of all process models) followed by process models 1-5,4,2 in that partly equal order. This order can be used as a prioritization if the aim is to prevent against impacts of events affecting machines.

Another result is that only one (process model 4) of the five process models is fully resource-redundant (with a MRD value of 1). This process model consists of paths with associated resources to be replaceable at least once in case of failures. This also means that

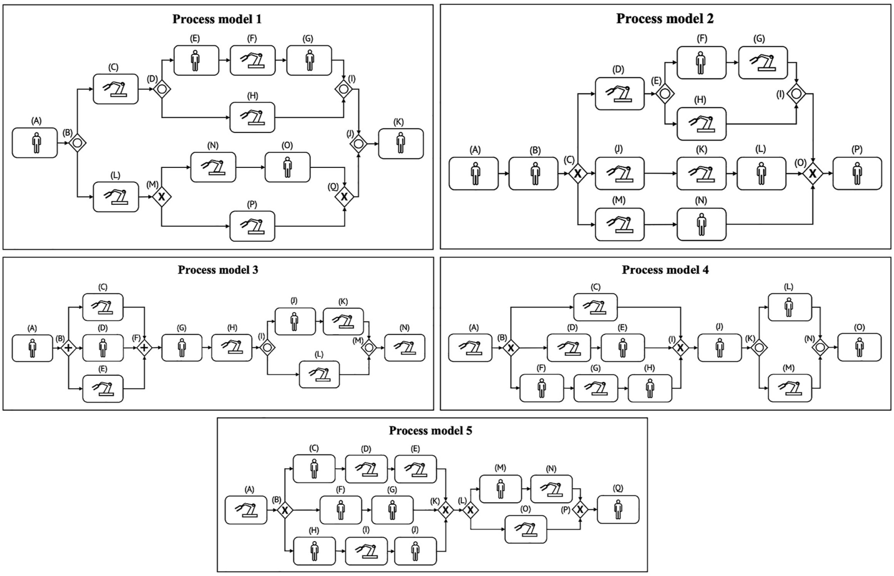

Figure 3.
Production and logistics process models

Table 4.
Resource models

Resource model 1	A	C	E	F	G	H	K	L	N	O	P
Assignable resources	4	2	3	3	5	2	5	2	1	4	2
Redundant resources (= assignable resources – 1)	3	1	2	2	4	1	4	1	0	3	1

Resource model 2	A	B	D	F	G	H	J	K	L	M	N	P
Assignable resources	2	2	2	2	1	2	2	2	2	2	2	2
Redundant resources (= assignable resources – 1)	1	1	1	1	0	1	1	1	1	1	1	1

Resource model 3	A	C	D	E	G	H	J	K	L	N
Assignable resources	2	3	5	6	7	8	1	9	5	6
Redundant resources (= assignable resources – 1)	1	2	4	5	6	7	0	8	4	5

Resource model 4	A	C	D	E	F	G	H	J	L	M	O
Assignable resources	2	3	4	5	6	5	3	3	2	4	3
Redundant resources (= assignable resources – 1)	1	2	3	4	5	4	2	2	1	3	2

Resource model 5	A	C	D	E	F	G	H	I	J	M	N	O	Q
Assignable resources	3	4	2	3	5	3	2	1	1	1	2	2	3
Redundant resources (= assignable resources – 1)	2	3	1	2	4	2	1	0	0	0	1	1	2

Table 5.
Results of production and logistics cases

	Process model 1	Process model 2	Process model 3	Process model 4	Process model 5
Human Intensity (HI)	0.51	0.66	0.41	0.58	0.51
Machine Intensity (MI)	0.49	0.34	0.59	0.42	0.49
Model Redundancy Degree (MRD)	0.64	0.60	0.33	1.00	0.33
Resource Redundancy Degree (RRD)	0.95	0.93	0.93	1.00	0.81
Resource Redundancy Intensity (RRI)	0.00	0.00	0.00	2.26	0.00

four of the five process models are vulnerable to some extent with respect to resource redundancy. Process models 3 and 5 are the most vulnerable ones in this respect (with MRD values of 0.33 for both) followed by process models 2 and 1 in that order. If the aim is to improve the resilience of process models by considering the resource redundancy of their paths, the order mentioned can be used as a prioritization.

Process model 5 is, in relative terms, the most vulnerable one if the resource redundancy of each node of all process paths is considered (lowest RRD value of all process models). This result can be used to prioritize process model 5 against process model 3 in case of deciding with which model to begin with resilience improvements (both having the same MRD value of

0.33). Thus, process model 5 followed by process models 2-3,1,4 in the partly equal order specified can be used as a prioritization for resource redundancy improvements.

5.3 Workshops

In this section, feedback received from professionals about the contributions proposed in this paper (life cycle and metrics in section 4.1 and 4.2) is summarized. The feedback was obtained by conducting workshops on two consecutive days with professionals working in different business process domains. The domain of expertise, years of domain working experience and the level of domain expertise for each workshop participant are depicted in Table 6.

The workshop participants can, on average, be considered as experienced in the field of resource and BPM. Two-thirds of the participants have a senior level of expertise, with 11 or more years of working experience in respective domains. Furthermore, for each domain, at least one participant has a senior level of expertise. The domains of expertise are quite diverse, ranging from rather business-focused process analysts to technical experts focused on manufacturing workflow technology. With this setting of mainly experienced participants having diverse domain expertise, the foundation for gaining valuable findings has been laid.

The following steps have been performed during the course of the workshop days: (1) introduction to the goals of the workshops and the general topic of process resilience, (2) explanation of the process resilience life cycle and metrics to participants, (3) selection of two process models and applying the process resilience metrics to it and (4) evaluation of the life cycle and metrics proposed with discussions of limitations and improvement potentials. In the following, the main workshop feedbacks are presented.

5.3.1 Transparency. The process resilience life cycle has been valued as a systematic and holistic way to start with analyzing possible vulnerabilities of business operations. Furthermore, the process resilience metrics have also been considered as valuable contributions toward an objective enterprise resilience measurement system.

5.3.2 Critical paths. The metrics are also valued for their ability to determine and assess critical process paths. Critical process paths are paths that have resource nodes with only one or none resources for execution. They are considered as bottlenecks of operations, as either a resource is not available for execution or a resource cannot be replaced in case of failure. Critical process paths are thus very important sources to disclose vulnerabilities to be solved for the aim of business continuity. Further measures for continuity like recoverability and rework of process items are also noted in this regard by some participants.

5.3.3 Independency. The metrics are further valued for their notation-independent definition and general applicability to any process modeling notation. This is seen as very advantageous as the metrics can also be applied if multiple notations are used in one

Participant	Domain of expertise	Years of domain experience	Level of domain expertise
1	Manufacturing resource planning	15	Senior
2	Manufacturing resource planning	3	Junior
3	Manufacturing resource planning	8	Intermediate
4	Business process analysis	13	Senior
5	Business process analysis	11	Senior
6	Business process analysis	2	Junior
7	Manufacturing execution	15	Senior
8	Manufacturing execution	11	Senior
9	Manufacturing workflow technology	14	Senior

Table 6.
Overview of workshop participants

organization. The organizational barriers to use the metrics are in this respect regarded as low.

5.3.4 Comparability. Another great advantage of the metrics is the ability to compare process models and paths by considering different resilience perspectives. As a result of this, prioritizations to improve enterprise resource allocations and investments based on resilience criteria can be determined. This is seen as a powerful enhancement for operational resilience decisions to be taken by enterprises.

5.3.5 Software support. The participants also stated that software support to conduct resilience analyses would be preferable. Two functionalities are regarded as quite important in this regard. Firstly, software systems should be able to automatically detect and represent resource redundancy data along design, planning and execution of workflows and business processes. Secondly, respective data should be visualized in real time using dashboards. Likewise, the software system should include an assisted step-by-step approach to prepare and conduct resilience analyses.

6. Managerial implications

In this section, managerial implications related to the research work presented in this paper are introduced. Managerial implications can be considered as possible actions related to the findings of this paper that can be initiated by management staff of organizations.

6.1 Awareness

Organizations should establish an environment that foster awareness toward resource failures and their impacts especially on core business processes. This can be achieved by appropriate communication and training of employees. Employees responsible for certain processes should especially be aware to consider resource redundancy starting by the design of processes and workflows.

6.2 Responsibility

Organizations should further assign responsibilities to suitable employees in order to enable them to deal with resilience issues. Employees need to be equipped in this respect with abilities and authorizations to evaluate resource failures and initiate measures as responses to reduce or eliminate possible impacts. Assignment of responsibilities to employees can be considered as a first vital step toward initiating following activities with the aim to handle resource failures.

6.3 Monitoring

Organizations should develop monitoring capabilities that are able to scan external and internal environments of organizations. Monitoring should in this respect be able to continually scan respective environments and be able to adapt in case environmental conditions change. External monitoring thereby aims to detect adverse events originating outside of organizations like natural disasters. Internal monitoring aims to search for unexpected behaviors of processes originating from resource failures.

6.4 Organizational learning

Organizational learning should be used to strengthen the resilience capabilities of organizations. Resource failures occurred can in this respect be used as sources of improvements to prepare for and avoid similar situations in the future. Insights gained from resource failures should be incorporated into organizational knowledge, and capabilities to act upon this knowledge need to be developed.

6.5 Culture

Organizations should further ensure an organizational culture with resilience embedded in their day-to-day operations. One important element in this regard can be the establishment of creative problem-solving capabilities where solution approaches considering resource failures of different extents are provided. Another important component in this context is to foster agility which means that a quick and appropriate response with regard to resource failures can be initiated.

6.6 Process thinking

Organizations should educate all employees toward process-related thinking. By doing so, employees can be enabled to consider chains of activities as processes with resource dependencies rather than only focusing on activities they are involved in. Furthermore, employees may also better understand why process-related resilience considerations like resource redundancy issues are important aspects of business continuity.

7. Conclusion

Adverse events can be unknown, unexpected and may seriously damage the functioning of any kind of system. The knowledge on how to prepare for and cope with events that may have negative effects on organizations is thus of crucial importance, especially if their existences are threatened.

Resilience is a concept that holds the promise to prepare for as well as to handle adverse events. It is valuable to use the concept for enterprises and examine business processes against their ability to absorb impacts of adverse events. The resources that are required for business process executions are of special interest in this regard.

In view of the above, enterprises are interested in how resilient process models and paths are by considering resources. To contribute to this question, a life cycle with five different stages has been proposed. Additionally, five quantitative metrics to measure the degree of resilience process models and paths possess by considering resources have been developed.

The life cycle and metrics can be used to support resilience-related decisions. The life cycle mainly serves to uncover different stages aiming to holistically begin with process resilience analysis. The metrics can, for example, be used to determine prioritizations for resource-related resilience improvements by comparing process models and paths. Furthermore, the metrics can indicate if bottlenecks of operations exist. Bottlenecks of operations are considered in this regard as process paths that are not completely resource-redundant.

The metrics can basically be applied independent from any process modeling notation used and are thus not limited in this respect. However, some prerequisites need to be considered if they are applied. For example, process models need to be available and fully specified at the time of calculating the metrics. If they are not fully specified, the metric results may not be useful for comparison. Additionally, process models need to be designed or adapted using a level of granularity to determine human and machine resources. This may not necessarily be the default case as process models can be modeled using various abstraction levels.

The life cycle and metrics have been validated in two ways. Firstly, the applicability of the metrics and related findings derived has been shown by using five real-world production and logistics cases. Secondly, workshops have been conducted with professionals to receive feedback about the added value and improvement suggestions for the life cycle and metrics proposed.

The life cycle and metrics are especially valued in terms of transparency, independency, comparability as well as the ability to determine and assess critical process paths by professionals. As a suggestion for improvement, software support to conduct resilience analyses has been mentioned.

References

Allen, J.H. (2011), "Measures for managing operational resilience", *The EDP Audit, Control, and Security Newsletter*, Vol. 44 No. 6, pp. 1-6.

Allen, J.H. and Curtis, P.D. (2011), "Measures for managing operational resilience", available at: https://resources.sei.cmu.edu/asset_files/TechnicalReport/2011_005_001_15407.pdf (accessed 30 March 2021).

Allen, J.H. and Davis, N. (2010), "Measuring operational resilience using the CERT® resilience management model", available at: https://resources.sei.cmu.edu/asset_files/TechnicalNote/2010_004_001_15203.pdf (accessed 28 March 2021).

Bhuiyan, M., Islam, M.M.Z., Koliadis, G., Krishna, A. and Ghose, A.K. (2007), "Managing business process risk using rich organizational models", *31st Annual International Computer Software and Applications Conference (COMPSAC 2007)*, IEEE, pp. 509-520.

Birkie, S.E., Trucco, P. and Kaulio, M. (2013), "State-of-the-Art review on operational resilience: concept, scope and gaps", in Emmanouilidis, C., Taisch, M. and Kiritsis, D. (Eds), *Advances in Production Management Systems. Competitive Manufacturing for Innovative Products and Services*, Springer, Berlin, pp. 273-280.

Caralli, R.A., Allen, J.H., Curtis, P.D., White, D.W. and Young, L.R. (2010), "Improving operational resilience processes", *2nd International Conference on Social Computing*, IEEE, pp. 1165-1170.

Cardoso, J., Mendling, J., Neumann, G. and Reijers, H.A. (2006), "A discourse on complexity of process models", in Eder, J. and Dustdar, S. (Eds), *Business Process Management Workshops*, Springer, Berlin, pp. 117-128.

Duchek, S. (2020), "Organizational resilience: a capability-based conceptualization", *Business Research*, Vol. 13 No. 1, pp. 215-246.

Dumas, M., La Rosa, M., Mendling, J. and Reijers, H.A. (2018), *Fundamentals of Business Process Management*, Springer, Berlin.

Erol, O., Mansouri, M. and Sauser, B. (2009), "A framework for enterprise resilience using service oriented architecture approach", *3rd Annual IEEE Systems Conference*, IEEE, pp. 127-132.

Erol, O., Devanandham, H., Sauser, B. and Mansouri, M. (2010), "Perspectives on measuring enterprise resilience", *2010 IEEE International Systems Conference*, IEEE, pp. 587-592.

Ferstl, O.K. and Sinz, E.J. (1998), "Modeling of business systems using SOM", Bernus, P., Mertins, K. and Schmidt, G. (Eds), *Handbook on Architectures of Information Systems*, Springer, Berlin, pp. 347-367.

Fraccascia, L., Giannoccaro, I. and Albino, V. (2018), "Resilience of complex systems: state of the art and directions for future research", *Complexity*, Vol. 2018, pp. 1-44, 3421529.

Furuta, K. (2015), "Resilience engineering", Ahn, J., Carson, C., Jensen, M., Juraku, K., Nagasaki, S. and Tanaka, S. (Eds), *Reflections on the Fukushima Daiichi Nuclear Accident*, Springer, Cham, pp. 435-454.

Gruhn, V. and Laue, R. (2006), "Complexity metrics for business process models", in Abramowicz, W. and Mayr, H. (Eds), *Business Information Systems – 9th International Conference on Business Information Systems (BIS 2006)*, Gesellschaft für Informatik e.V., Bonn, pp. 1-12.

Haimes, Y.Y. (2009), "On the definition of resilience in systems", *Risk Analysis*, Vol. 29 No. 4, pp. 498-501.

Hillmann, J. and Guenther, E. (2021), "Organizational resilience: a valuable construct for management research?", *International Journal of Management Reviews*, Vol. 23 No. 1, pp. 7-44.

Lee, J., Lee, S., Kim, J. and Choi, I. (2019), "Dynamic human resource selection for business process exceptions", *Knowledge and Process Management*, Vol. 26 No. 1, pp. 23-31.

Li, H., Yang, Y. and Chen, T.Y. (2004), "Resource constraints analysis of workflow specifications", *Journal of Systems and Software*, Vol. 73 No. 2, pp. 271-285.

Linnenluecke, M.K. (2017), "Resilience in business and management research - a review of influential publications and a research", *International Journal of Management Review*, Vol. 19 No. 1, pp. 4-30.

Mendling, J. (2008), *Metrics for Process Models*, Springer, Berlin.

Object Management Group (2013), "Business process model and notation (BPMN) - version 2.0.2", available at: https://www.omg.org/spec/BPMN (accessed 13 June 2021).

Ougaabal, K., Zacharewicz, G., Ducq, Y. and Tazi, S. (2020), "Visual workflow process modeling and simulation approach based on non-functional properties of resources", *Applied Sciences*, Vol. 10 No. 13, pp. 1-24.

Paul, S.K. and Chowdhury, P. (2020), "Strategies for managing the impacts of disruptions during COVID-19: an example of toilet paper", *Global Journal of Flexible Systems Management*, Vol. 21 No. 3, pp. 283-293.

Ruiz-Martin, C., López-Paredes, A. and Wainer, G. (2018), "What we know and do not know about organizational resilience", *International Journal of Production Management and Engineering*, Vol. 6 No. 1, pp. 11-28.

Russell, N., van der Aalst, W.M.P., ter Hofstede, A.H.M. and Edmond, D. (2005), "Workflow resource patterns: identification, representation and tool support", in Pastor, O. and Falcão e Cunha, J. (Eds), *Advanced Information Systems Engineering*, Springer, Berlin, pp. 216-232.

Russell, N., van der Aalst, W.M.P. and ter Hofstede, A.H.M. (2016), *Workflow Patterns: The Definitive Guide*, MIT Press, Cambridge, Massachusetts.

Sahebjamnia, N., Torabi, S.A. and Mansouri, A. (2018), "Building organizational resilience in the face of multiple disruptions", *International Journal of Production Economics*, Vol. 197, pp. 63-83.

Salnitri, M., Dalpiaz, F. and Giorgini, P. (2017), "Designing secure business processes with SecBPMN", *Software and Systems Modeling*, Vol. 16 No. 3, pp. 737-757.

Sanchis, R., Canetta, L. and Poler, R. (2020), "A conceptual reference framework for enterprise resilience enhancement", *Sustainability*, Vol. 12 No. 4, pp. 1-27.

Sheffi, Y. and Rice, J.B. Jr (2005), "A supply chain view of the resilient enterprise", *MIT Sloan Management Review*, Vol. 47 No. 1, pp. 41-48.

Snedaker, S. and Rima, C. (2014), *Business Continuity and Disaster Recovery Planning for IT Professionals*, Syngress, Boston.

Thoma, K., Scharte, B., Hiller, D. and Leismann, T. (2016), "Resilience engineering as part of security research: definitions, concepts and science approaches", *European Journal for Security Research*, Vol. 1 No. 1, pp. 3-19.

Tierney, K. and Bruneau, M. (2007), "Conceptualizing and measuring resilience", *TR NEWS*, No. 250, pp. 14-17.

van Looy, A. and Shafagatova, A. (2016), "Business process performance measurement: a structured literature review of indicators, measures and metrics", *SpringerPlus*, Vol. 5, 1797.

Vanderfeesten, I., Cardoso, J., Mendling, J., Reijers, H.A. and van der Aalst, W. (2007), "Quality metrics for business process models", in Fischer, L. (Ed.), *BPM and Workflow Handbook*, Future Strategies, Lighthouse Point, pp. 179-190.

Vogus, T.J. and Sutcliffe, K.M. (2007), "Organizational resilience: towards a theory and research agenda", *International Conference on Systems, Man and Cybernetics*, IEEE, pp. 3418-3422.

Weske, M. (2012), *Business Process Management: Concepts, Languages, Architectures*, Springer, Berlin.

Winkler, U., Gilani, W., Guitman, A. and Marshall, A. (2012), "Models and methodology for automated business continuity analysis", in Perseil, I., Breitman, K. and Pouzet, M. (Eds), *17th IEEE International Conference on Engineering of Complex Computer Systems*, IEEE, Paris, pp. 57-64.

Zahoransky, R.M., Brenig, C. and Koslowski, T. (2015), "Towards a process-centered resilience framework", *10th International Conference on Availability, Reliability and Security*, IEEE, pp. 266-273.

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