Measuring and Analysing Resilience of Enterprise Architectures

Tjo-Kin Man
University of Twente
PO Box 217, 7500 AE Enschede
the Netherlands
t.man@student.utwente.nl

ABSTRACT
As business environments are increasingly dynamic and are changing rapidly, enterprise architectures have to be more resilient by design in order to cope with disruptions in an efficient and effective way. Although the literature provides multiple suggestions for achieving this, there is a need to assess how resilient an existing enterprise architecture is, what kind of changes are necessary and what the effects of these changes are. Hence, this study has the aim to create a framework – consisting of factors and metrics – which could be used to measure and analyse the resilience of enterprise architectures. The factors and metrics were identified and defined based on a systematic literature review, inferring factors and metrics from other contexts into the context of enterprise architectures. It seems that resilience in this context should be considered as an attribute which could be achieved by four connected abilities: anticipate, monitor, learn and respond. Four factors were identified (vulnerability to risks, agility, adaptability and robustness) which all contribute to at least one of these abilities comprising a process causing resilience. For some of the factors, metrics were also identified.

Keywords
Resilient Enterprise Architectures, Measuring Resilience, Enterprise Architecture, Resilience

1. INTRODUCTION
In an era of network-centric communication, digitised information and intelligent manufacturing technologies, business environments are increasingly dynamic and are changing rapidly. The number and types of causes of business disruptions are growing continuously: climatic and geophysical disasters, (geo-)political instability, cyber-attacks, regulatory reformations, etc. [1] These digital transformations and disruptions impact enterprises [12], creating opportunities but also threats and uncertainties in the already highly competitive and complex global business environments [3][9]. It is no longer a matter of if but when some event will threaten or cause major disruptions in any enterprise [1].

As it is increasingly difficult for an organisation to avoid or eliminate all the potential vectors of business disruptions [1], there is a need for enterprises to deal with disruptions, to adapt to turbulent environments, to cope with emerging threats, and to rapidly satisfy emerging business needs and stakeholders [3]. This requires more resilient enterprise architectures by design.

In the literature, there are multiple suggestions which are all claimed to be possibly effective in achieving more resilient enterprise architectures. For instance, Gallopin [4] suggests to decrease the complexity of enterprise infrastructures while Gomes [5] suggests to embrace a Service Oriented Architecture approach when designing enterprise architectures. In itself, all these suggestions may contribute to more resilient enterprise architectures. However, for any of these suggestions to be practically meaningful, there is a need to assess how resilient an existing enterprise architecture is, what kind of changes are necessary and what the effects of these changes are. Hence, there is a need for an instrument to measure and analyse the resilience of enterprise architectures.

Currently, such an instrument does not exist and there are no research results which could be used to create such an instrument. Due to the novelty of this research area, there are no studies available which are concerned with measuring and analysing the resilience of specifically enterprise architectures. To take the first steps towards closing this gap, the goal of this novel study is to create a framework – consisting of factors and metrics – which could be used to measure and analyse the resilience of enterprise architectures. As no research on this domain has been done, this will be an inductive research with an exploratory, qualitative character. A systematic literature review, following the guidelines and the processes proposed by Kitchenham [6], will be conducted with the aim to infer factors and metrics from other contexts into the context of enterprise architectures.

Chapter 2 elaborates on the research methodology by providing and explaining the research questions, the search process, the selection criteria and the quality assessment questions. Chapter 3 presents the findings of the literature review, discusses the results of this study, and answers the research subquestions by proposing the intended framework. Chapter 4 concludes this study by answering the research question and by discussing the created framework, the limitations of this study and the possible future directions.

2. METHODOLOGY
The steps taken in the systematic literature review, following the guidelines and the processes proposed by Kitchenham [6], are documented and elaborated in the following sections.

2.1 Research Questions and Scope
The research question addressed by this study is:

RQ1 How can the resilience of enterprise architectures be measured and analysed?

To answer this question, it is necessary to have a clear and conclusive definition of the construct resilience in the context of enterprise architectures. This gives subquestion 1.

31th Twente Student Conference on IT, July. 5th, 2019, Enschede, The Netherlands.

RQ1.1 What is the definition of resilience in the context of enterprise architecture?

After having this definition, the mutually exclusive factors which may impact the resilience of enterprise architectures have to be identified and clearly defined. This gives subquestion 2.

RQ1.2 What mutually exclusive factors influence the resilience of enterprise architectures?

Finally, for these factors to be practically applicable, these should be made measurable and analysable by identifying operational metrics. This gives subquestion 3.

RQ1.3 What are the metrics which make the identified factors of RQ1.2 measurable and analysable?

2.2 Search Process

Scopus is used to manually search for primary studies. The goal of this literature review is to define resilience in the context of enterprise architectures, and to identify and define the factors and the corresponding metrics which are influencing the resilience of enterprise architectures. Also, it has the purpose of explaining the relationships between the identified factors (IVs) and the construct resilient enterprise architectures (DV).

Due to the lack of research on resilience in the context of enterprise architectures, the literature review focusses not merely on this context. Resilience is a multifaceted and multidimensional concept, covering many disciplines such as strategic management, human resource management and disaster management [5]. Therefore, this literature review also focusses on other contexts with the goal to infer factors and metrics from these other contexts into the context of enterprise architectures.

2.3 Contexts and Selection Criteria

For this study, any context could be relevant to infer factors and metrics from. However, to narrow the search scope, the focus is on resilience in the context of enterprise, management and organisational architectures. The last two contexts are chosen because of the close connection with enterprise architectures. This gives the following Scopus search query, searching in the title, abstract and keywords: TITLE-ABS-KEY (resilien* AND enterprise OR management OR organisation AND architecture). 1258 documents are found. After applying a filter for only English and final publications, Scopus returns 1229 documents. Adding a filter to search for the terms *factor* or *indicator* in all fields, Scopus returns 185 documents. Applying a similar filter with the terms *metric* or *measure** results in 81 documents. A numerical analysis of the 81 documents is included in Appendix A.

The abstracts of these 81 documents are read. Based on the abstracts, the following information about the documents is collected and presented in table 1 of Appendix A:

- The context in which resilience is discussed.

Cr1. Whether it provides a definition of resilience.

Cr2. Whether it identifies factors influencing resilience.

Cr3. Whether it provides metrics for the identified factors.

14 of the 81 documents seem to meet at least one of the criteria (Cr). After reading the 14 documents, 6 documents are selected for this study as these meet the criteria the most and are discussing resilience in relatable domains. The criteria assessment of the 6 documents is presented in table 2. The deviations between the information presented in table 1 and 2 is a result of advancing insights gained after reading the full documents. The study inclusion and exclusion process is graphically depicted in figure 1.

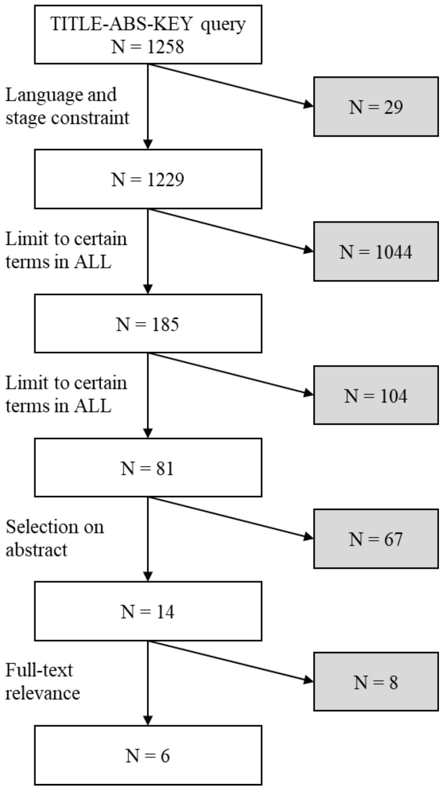

Figure 1. Study inclusion and exclusion process

2.4 Quality Assessment

The studies which are selected for this research (table 2) are evaluated based on the following quality assessment questions:

QA1. Are the factors and/or metrics properly defined?

QA2. Are the factors and/or metrics context-independent?

QA3. Are the factors and/or metrics theoretically grounded?

QA4. Are the factors and/or metrics validated?

QA1 has the purpose of determining the completeness of the definitions, necessary to differentiate similar factors/metrics and to create understanding. QA2 has the purpose of assessing the generalisability of the factors/metrics, necessary for the application in the context of enterprise architectures. QA3 and QA4 have the purpose of assessing the quality of the factors/metrics, possibly explaining the differences between studies and guiding the strength of the inferences.

The questions were scored as follows:

- QA1: Y (yes), the definitions are complete, explicit and mutually exclusive. P (partly), the definitions are complete but implicit or overlapping. N (no), else.
- QA2: Y, the factors/metrics can be applied in different, non-related, contexts. P, the factors/metrics can be applied in different, but related, contexts. N, else.
- QA3: Y, >= 2 different academic sources confirmed every factor/metric. P, one academic source or >=2 non-academic sources confirmed every factor/metric. N, else.
- QA4: Y, the factors/metrics are statistically validated. P, the factors/metrics are empirically validated. N, else.

All questions have the same weight. Y gives 1 point, P gives 0.5 points and N gives zero points.

Table 2. Criteria assessment of the selected studies

#	Authors	Title	Year	Context	Cr1	Cr2	Cr3
1	De Vrieze P., Xu L. [2]	Resilience analysis of service-oriented collaboration process management systems	2018	Business process mgt.	X	X	X
2	Erol O., Mansouri M., Sauser B. [3]	A framework for enterprise resilience using service oriented architecture approach	2009	Enterprises	X	X	
3	Ouedraogo K.A., Enjalbert S., Vanderhaegen F. [7]	How to learn from the resilience of Human-Machine Systems?	2013	Human-machine systems	X	X	X
4	Pasquini A., Ragosta M., Herrera I.A., Vennesland A. [8]	Towards a measure of Resilience	2015	Air traffic management	X	X	X
5	Ungar M. [10]	Systemic resilience: principles and processes for a science of change in contexts of adversity	2018	Systems	X	X	
6	Vallance S. [11]	An Evaluation of the Waimakariri District Council's Integrated and Community-Based Recovery Framework Following the Canterbury Earthquakes: Implications for Urban Resilience	2015	Disaster management	X	X	

Table 3. Factors found in the selected studies

#	Context	Factor(s)
1	Business process mgt.	• Ability to accommodate changes • Speed of recovery • Replaceability of services • Elasticity of service provision
2	Enterprises	• Process: preparation, occurrence of a disruptive event, first response, initial impact, time of full impact, preparation for recovery, recovery, and long term impact. • Level of vulnerability to risks • Adaptive capacity: robustness, agility, adaptability, flexibility • Efficiency
3	Human-machine systems	• 4 quantities (process): anticipate, monitor, respond, learn • Speed of recovery, Maximum recovery ability
4	Air traffic management	• 4 essential abilities (process): anticipate, monitor, respond, learn • Entity of changes and disturbances • Deviations from optimal performances
5	Systems	• Process: persistence, resistance, recovery, adaptation, transformation • Openness to new information, connectivity with other entities • Experimentation, learning • Diversity, redundancy, participation
6	Disaster management	• 4 R's (process): reduction, readiness, response, recovery • Holistic and integrated recovery: mandate, local knowledge, pre-existing relationships, control/own resources • Appropriate leadership • Adaptive capacity: flexibility, over-capacity • Emphasis on symbolic, expectative and participative dimensions

Table 4. Quality evaluation of the selected studies

	Factors					Metrics				
#	QA1	QA2	QA3	QA4	Score	QA1	QA2	QA3	QA4	Score
1.	N	P	N	N	0.5	Y	Y	N	P	2.5
2.	P	Y	Y	N	2.5	-	-	-	-	-
3.	P	P	P	N	1.5	Y	P	N	P	2.0
4.	Y	Y	N	N	2.0	Y	Y	N	N	2.0
5.	Y	Y	Y	P	3.5	-	-	-	-	-
6.	Y	P	P	P	2.5	-	-	-	-	-

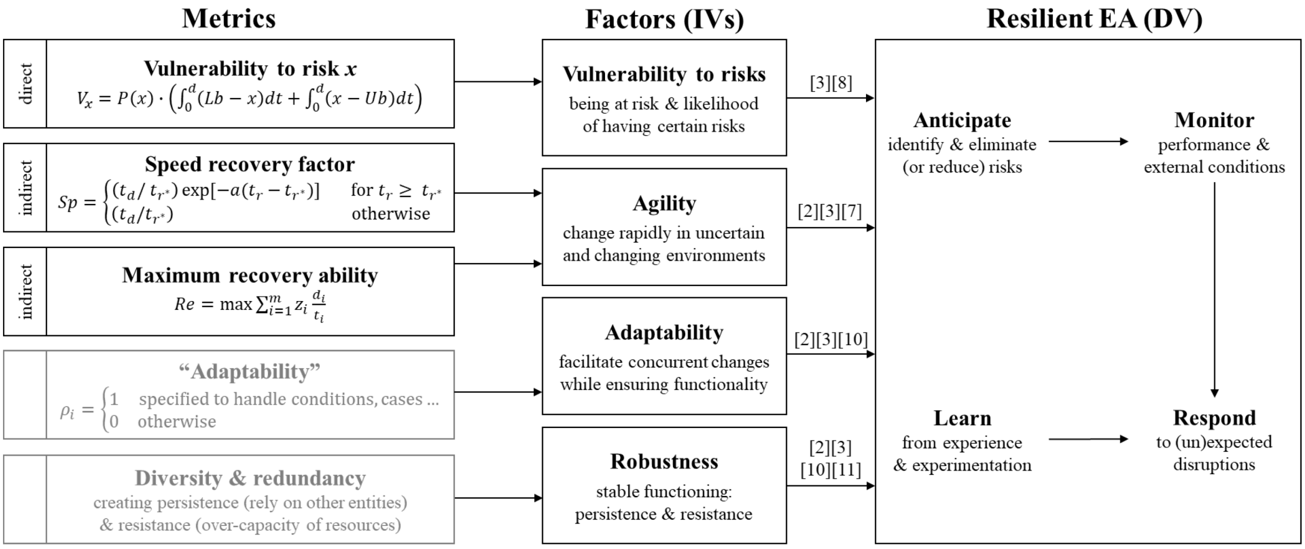

Figure 2. Framework for measuring and analysing the resilience of enterprise architectures

3. RESULTS

This section discusses the relevant findings of the systematic literature review and answers the subquestions of this study.

Table 3 presents the factors found in the literature review. These are all the factors which are influencing resilience in the contexts of the originating studies. Related or similar factors are grouped together.

Table 4 presents the outcomes of the quality evaluation of the selected studies. Since the evaluation outcomes are different for the factors and the metrics, these are assessed separately for every question. The sequence numbers (#) in tables 3 and 4 correspond with the sequence numbers in table 2

3.1 Resilient Enterprise Architectures

To provide a definition of resilience in the context of enterprise architectures (RQ1.1), the concepts *enterprise architecture* and *resilience* will be discussed first in isolation. Then, resilience will be discussed in the broad context of enterprises. Finally, the relation with the subcontext enterprise architectures will be made which eventually results in a derived definition of resilience in the context of enterprise architectures.

3.1.1 Enterprise Architecture

An enterprise architecture is a high-level and complete expression of an enterprise [3][5]. It defines the key strategies, usually in the domains of business, organisation, applications and technologies, and in terms of their impact on its processes and functions [5]. This holistic approach integrates the technical system components with the human stakeholders [8], providing a common view of the primary resources (people, processes, data and technology), and how they integrate to provide the primary drivers of an enterprise [3][5].

3.1.2 Resilience

In most literature, resilience is described as an inherent attribute of complex systems [3]. Originally, this construct is developed in the field of ecology and is used to characterise the tendency of natural systems to maintain their integrity when subjected to disturbances [7]. More generally, it is an expression for the ability of systems to withstand unanticipated failures without catastrophic losses [2][3]; i.e. returning to an equilibrium [10] prior, during or following changes and disturbances [8]. Adapted from systems theory [10], resilience is in this study defined as an inherent ability of complex systems to anticipate, adapt and reorganise itself under disruptive conditions in ways that promote and sustain its functioning.

3.1.3 Enterprise Resilience

The scope and interpretation of resilience is context dependent. In the broad context of enterprises, resilience is a widely used term [3]. Zimmermann and Schmidt [12] describe enterprise resilience as an emergent expression for the capability of systems to cope with fast and real-time changing events. Gallopin [4] defines it as an enterprise's adaptive capacity and its ability to cope with, adapt to, and recover from a disruption. Sheffi and Rice [9] discuss enterprise resilience as a function, a strategic initiative of enterprises that change the way of operation and with it, the competitive position and the responsiveness to threats. This includes the ability of enterprises to bounce back when a disruption occurs (i.e. returning to an equilibrium). Hence, for this study, enterprise resilience is defined as the ability of enterprises to adapt to, bounce back and recover from real-time changing disruptions.

3.1.4 Resilient Enterprise Architectures

In the subcontext of enterprise architectures, resilience can be defined based on the definition of enterprise resilience. By analogy with the definition of resilience in the context of business process management [2], resilience in the context of enterprise architectures can be defined as a combination of two aspects. First are the properties of an enterprise architecture which intrinsically allow the integration of the technical system components and the human stakeholders to adapt to or bounce back from any real-time changing disruption. The second aspect is the recovery profile of an enterprise architecture: the extent to which an enterprise architecture is designed to reduce the impact of disruptions over time.

3.2 Factors and Metrics

This section identifies and discusses the relevant factors which may influence the resilience of enterprise architectures (RQ1.2). Where available, the metrics which make the identified factors analysable and measurable are also provided and discussed (RQ1.3). These factors, metrics and their relation to resilient enterprise architectures (EA) construct the framework depicted in figure 2.

This framework is created in an iterative process of aggregation and transformation. That is, the findings presented in table 3 are first aggregated into larger units of mutually exclusive factors. Then, these factors are transformed such that they are applicable in the specific context of enterprise architectures. Finally, the metrics are identified which make the factors measurable and analysable. All the elements of this framework are discussed in this section. The studies which constitute the causal relationships between the factors (IVs) and the construct resilient EA (DV) are indicated in the framework.

Notice that "measurable and analysable" in RQ1.3 does not necessarily implicate that the identified metrics are intrinsically meaningful. The metrics only have the purpose of making the identified factors operational.

3.2.1 Resilience as a Process

Before discussing the factors which are influencing the resilience of enterprise architectures, is it important to note that 5 of the 6 included studies consider resilience as a process rather than a static attribute. These studies [3][7][8][10][11] claim that resilience can only be achieved if certain abilities are intrinsically present in a system. Hence, it is arguable that the factors influencing resilience are not directly affecting it. Instead, it is likely that the factors are contributing to certain connected abilities which comprise a process causing resilience.

The process for resilient enterprise architectures (EA), as depicted in figure 2, is adapted from resilience engineering [7][8] and supplemented with elements from disaster management [11] and systems theory [10].

Anticipate refers to the ability enterprise architectures create to anticipate to – identify and eliminate or reduce [11] – risk events [7][8]. This is not only about isolated events but also how entities may interact and affect each other [8].

Monitor refers to the ability enterprise architectures create to monitor own performance and external conditions focussing on what is essential to continue operations [7][8]. This increases the readiness of enterprises before a disruption occurs [11].

Learn refers to the ability enterprise architectures create to learn from experience [7][8][10] and from experimentation [10] by understanding what happened in past events [8] and by integrating learning into future efforts [10].

Respond refers to the ability enterprise architectures create to respond timely to expected and unexpected disruptions in a robust and flexible manner [7][8][11]. This could be recovery, adaptation or both. Recovery is the process of returning to a previous state [10] (i.e. to bounce back) while adaptation is the process of adjusting to a new way of functioning [10].

All four abilities are connected. That is, for the ability *monitor* or *learn* to contribute to resilience, an enterprise has to *respond* based on what is monitored and/or learned. Also, for the ability *anticipate* to contribute to resilience, an enterprise has to *monitor* whether something anticipated is happening and *respond* to it. As all abilities are eventually contributing to the ability *respond,* this ability is central in this process. Therefore, the definition of *respond* is complementary to the definition of *resilient enterprise architectures* (see section 3.1.3).

3.2.2 Factor: Vulnerability to Risks

The first identified factor is the architecture's vulnerability to risks. This could be defined as being at risk and the likelihood of having certain risks [3], possibly causing disturbances [8].

This factor is relevant since it contributes to the abilities *anticipate, learn* and *monitor*. Constitutive for *anticipation* and *learning* is the identification of the risk events, their likelihood and their effects – in isolation and in relation to other entities. In other words, it should be known what, how likely and what the consequences of these risks are in order to eliminate, reduce or learn from them. At the same time, it should be *monitored* whether an architecture is at risk and how external conditions may affect certain risks. This is necessary for an enterprise to *respond* timely in a robust and flexible manner.

The commonly used metric for measuring the vulnerability of risk x (V_x) is the product of the probability of the occurrence of x $\left(P(x)\right)$ and the level of its consequences $\left(C(x)\right)$ [3][9]:

$$V_x = P(x) \cdot C(x)$$

Although this formula is universally applicable, "the level of consequences" is a vague factor which could be interpreted in many different ways. For enterprise architectures, it is the extent and duration of the disruptions which impact their resilience (i.e. constitutes their recovery profiles). Adapted from systems theory [8], the disruption of an enterprise architecture caused by risk x (D_x) with duration d can be expressed as a summation of two integrals. Here, the distances from the lower and upper critical boundaries (Lb and Ub) represent the magnitude of the disruptions while the area measures their extent, "the level of consequences":

$$D_x = \int_0^d (Lb - x)dt + \int_0^d (x - Ub)dt$$

This allows the vulnerability to risk x to be measured by:

$$V_x = P(x) \cdot D_x = P(x) \cdot \left(\int_0^d (Lb - x)dt + \int_0^d (x - Ub)dt \right)$$

Where:

V_x = vulnerability to risk x (lower is better)
$P(x)$ = chance of occurrence of risk x
d = duration of the disruption
Lb = lower boundary of normal range
Ub = upper boundary of normal range

3.2.3 Factor: Agility

The second identified factor is the agility of enterprise architectures. This could be defined as the ability to change rapidly in an uncertain and changing environment [3].

This factor is relevant since it contributes to a timely and fast response in rapidly changing environments [3]. This is an integral part of the ability *respond*, as the more agile enterprise architectures are, the faster enterprises could be recovered or adapted [2][7] in a robust and flexible manner.

The agility of enterprise architectures cannot be measured directly as agility could be affected by an infinite number of interdependent aspects. Nevertheless, the consequences of agility can be measured, giving indirect measures for agility.

The first indirect metric for agility is the speed recovery factor (Sp) [2]. This metric is a measure of the speed at which an equilibrium point is exceeded such that a disruption does not cause further performance degradation. In other words, the speed recovery factor is a measure for the speed at which an enterprise architecture can be recovered. Although not explicitly defined, this metric might also be applicable to measure adaptation.

$$Sp = \begin{cases} (t_d/\, t_{r^*}) \exp[-a(t_r - t_{r^*})] & \text{for } t_r \geq t_{r^*} \\ (t_d/t_{r^*}) & \text{otherwise} \end{cases}$$

Where:

Sp = speed recovery factor (higher is better)

t_d = slack time, i.e. maximum acceptable time to post-disruption before ensuring recovery

t_r = time to final recovery

t_{r^*} = time to complete initial recovery actions

a = parameter controlling decay in resilience attributable to time to new equilibrium

The second indirect metric for agility is the maximum recovery ability (Re), adapted from resilience in the context of partly damaged information systems [7]. This metric is a measure for the extent (i.e. how many entities of) an enterprise architecture can be recovered within the demanded time. Although not explicitly defined, this metric might also be applicable to measure adaptation.

$$Re = \max \sum_{i=1}^{m} z_i \frac{d_i}{t_i}$$

Where:

Re = maximum recovery ability (higher is better)

d_i = demand time for the recovery of part i; $(i = 1, \dots, m)$

m = number of entities in the enterprise architecture

t_i = time to final recovery of part i

z_i = weight of part i, representing its importance and such that: $\sum_{i=1}^{m} z_i = 1$

3.2.4 Factor: Adaptability

The third identified factor is the adaptability of enterprise architectures. This could be defined as the ability to facilitate concurrent (parallel) changes, allowing accommodations to changing business environments and requirements while the delivery of the intended functionality is ensured [2][3][10].

This factor is relevant since it contributes to the abilities *anticipate, learn* and *respond*. For enterprises to *anticipate* to risk events or *learn* by experimentation, enterprise architectures have to be adaptable without current processes being negatively affected. In other words, enterprises require the ability to facilitate concurrent changes, allowing risk mitigation or experimentation on the one hand and business continuity on the other hand. Also, for enterprises to *respond* in a flexible manner, adaptability of enterprise architectures allow enterprises to change specific entities of the architecture without affecting other entities.

As both adaptability and its consequences are having a very qualitative nature, no metrics were identified which could be used to measure them qualitatively. An, yet unsophisticated, attempt was found in the study of De Vrieze and Xu [2], who suggested the following:

$$\rho_i = \begin{cases} 1 & \text{specified to handle conditions, cases, exceptions} \\ 0 & \text{otherwise} \end{cases}$$

3.2.5 Factor: Robustness

The fourth and last identified factor is the robustness of enterprise architectures. This could refer to persistence or resistance, both having the goal of maintaining a stable functioning as a result of large flexibility and insensitivity towards changing environments [2][3][10][11]. With persistence is meant that disruptions are avoided because of the passive supports enterprise architectures have [10]. With resistance, the same is achieved but by actively using other existing entities of the architecture [10].

This factor is relevant since it contributes to the ability *anticipate.* By maintaining a stable functioning of the enterprise architectures, enterprises could prevent or minimise the chance of disruptions from happening, i.e. eliminate or reduce risk events.

Similar to adaptability, robustness and its consequences are having a very qualitative nature. However, the literature shows a strong tendency towards two "good practices" for achieving robustness. Authors from different contexts argue that diversity and redundancy are key for robustness. In systems theory [10], having components that are ready to take over when one part of a system fails, is argued to be imperative for resilience. Here, resistance is created by diversity: providing systems with sufficient resources to rely on. Persistence is created by redundancy: resources and capacity are over-present and thus can be used in case of disruptions. In disaster management [11], over-capacity is recognised as a driver for flexibility as it allows key infrastructures and services to be taken over by other service providers. In business process management [2], services are considered to be more resilient if they can easily be replaced with other services (i.e. diversity gives resistance) or other service providers (i.e. redundancy gives persistence).

4. CONCLUSION AND DISCUSSION

In this study, a systematic literature review was conducted in an attempt to create an initial theoretical model of resilient enterprise architectures. As an artefact, a framework is created – consisting of factors and metrics – which could be used to measure and analyse the resilience of enterprise architectures. The created framework, as depicted in figure 2, consists of three parts: *resilient enterprise architecture* as the dependent variable, the factors influencing the resilience of enterprise architectures as the independent variables, and the metrics which make the identified factors measurable and analysable.

In this study, resilience in the context of enterprise architectures is considered as an attribute which could be achieved by four connected abilities: *anticipate*, *monitor*, *learn* and *respond.* Consequently, all identified factors contribute to at least one of these abilities comprising a process causing resilience. The first identified factor is the *vulnerability to risks*, defined as being at risk and the likelihood of having certain risks. This factor contributes to the abilities *anticipate, learn,* and *monitor,* and can be measured directly by the metric *Vulnerability to risk x*. The second identified factor is *agility*, defined as the ability to change rapidly in an uncertain and changing environment. This factor contributes to the ability *respond* and can be measured indirectly by the metrics *speed recovery factor* and *maximum recovery ability*. The third identified factor is *adaptability*, defined as the ability to facilitate concurrent (parallel) changes while the delivery of the intended functionality is ensured. This factor contributes to the abilities *anticipate*, *learn* and *respond*. No proper metrics were found for this factor because of its very qualitative nature; an unsophisticated attempt to a measure is included in the framework. The fourth factor is *robustness*, defined as maintaining a stable functioning as a result of large flexibility and insensitivity towards changing environments. This factor contributes to the ability *anticipate*. Also for this factor, no proper metrics were found because of its very qualitative nature. However, *diversity* and *redundancy* are frequently argued to be key to achieving robustness.

In this study, the first steps are taken in the creation of a framework for measuring and analysing the resilience of enterprise architectures. For this framework to be operational in a meaningful way, the issues with and the limitations of this study have to be overcome in future research. First, the factors and metrics of this study are not validated in every respect. Combined with the fact that the studies on which this study is based (almost) did not validate the factors and metrics either, the external validity could be considered as low. In order to build upon the outcomes of this study, validation is required. For example, one could consider conducting an empirical research in which this framework is applied to different enterprise architectures of which the resilience, relative to each other, is known. The second issue, related to the first issue, is that this framework is clearly lacking metrics measuring the effectiveness of the factors on the resilience of enterprise architectures. Therefore, metrics need to be identified which could measure the performance of the process (abilities) comprising resilient enterprise architectures. Perhaps, existing process performance indicators could be used. The third issue is the completeness of the framework. Although the aim of this exploratory research is not to be conclusive in identifying and defining the factors and metrics, it is almost self-evident that many more factors and metrics exist given the broadness of the construct resilient enterprise architectures. Further research, perhaps empirical, is necessary to identify and (further) define the factors and metrics influencing the resilience of enterprise architectures. Finally, it is doubtful whether enterprises will be able to apply this framework (or any framework) to their enterprise architectures. Especially with the identified metrics, these could be perceived as too specific or too broad/vague given their scattered origin in business process management, air traffic management and systems theory. This makes the operationalisation of the framework not very specific to enterprise architectures. In fact, the identified metrics are currently more suitable for measuring enterprise resilience (as a system) rather the resilience of enterprise architectures. Metrics which are specifically designed for enterprise architectures might be more sophisticated.

As an alternative to designing metrics specifically for enterprise architectures, it is very likely that other contexts than those covered by this study will give other metrics. For instance, heterogeneity might be a more direct way to measure the agility of enterprise architectures. This concept, originated from information technology, refers to the extent networks are open to different types of computer (components). For enterprise architectures, heterogeneity could be a measure for the extent to which the existing dependencies between entities can be replaced within a reasonable amount of time. If an enterprise architecture allows its entities to be replaced very easily, e.g. by adopting an approach similar to SOA, it can change very quickly. Therefore, it is arguable that an enterprise architecture with a high level of heterogeneity will also have a high level of agility. Another example of a more sophisticated metric is cyclomatic complexity, suitable for measuring the adaptability of enterprise architectures. This metric, originated from software science, is a measure for the complexity of any system of connected entities (i.e. nodes and edges). Cyclomatic complexity is calculated using the number of nodes, the number of edges and the number of externally connected components. For enterprise architectures, a low cyclomatic complexity means that their entities have a few or no internal and external dependencies. Therefore, it is likely that entities of an enterprise architecture with a low cyclomatic complexity could be adapted without (many) other entities being affected; the relationship with many other entities simply does not exist.

It is clear that this study is primarily attempting to create a conceptual foundation of resilient enterprise architectures. A lot of further research is necessary to validate, further concretise, complete and operationalise this construct.

5. ACKNOWLEDGEMENT

I am profoundly grateful to my supervisor Maria Iacob for her constructive support and the insightful conversations we had.

REFERENCES

[1] Berry, D., Hayward, B., Heneghan, L., Snyder, M. and Tjon, G. 2015. *Architecting the Resilient Enterprise--Are You Ready for failure?*.

[2] De Vrieze, P. and Xu, L., 2018. Resilience analysis of service-oriented collaboration process management systems. *Service Oriented Computing and Applications 12*, 1, 25-39. DOI= http://dx.doi.org/10.1007/s11761-018-0233-5.

[3] Erol, O., Mansouri, M., and Sauser, B., 2009. A framework for enterprise resilience using service oriented architecture approach. In *2009 3rd Annual IEEE Systems Conference*, 127-132. DOI= http://dx.doi.org/10.1109/SYSTEMS.2009.4815785.

[4] Gallopín, G.C., 2006. Linkages between vulnerability, resilience, and adaptive capacity. *Global Environmental Change 16*, 3 (2006/08/01/), 293-303. DOI= http://dx.doi.org/10.1016/j.gloenvcha.2006.02.004.

[5] Gomes, R., 2016. *Resilience and enterprise architecture in SMEs*.

[6] Kitchenham, B., 2007. *Kitchenham, B.: Guidelines for performing Systematic Literature Reviews in software engineering. EBSE Technical Report EBSE-2007-01*.

[7] Ouedraogo, K.A., Enjalbert, S., and Vanderhaegen, F., 2013. How to learn from the resilience of Human-Machine Systems? *Engineering Applications of Artificial Intelligence 26*, 1, 24-34. DOI= http://dx.doi.org/10.1016/j.engappai.2012.03.007.

[8] Pasquini, A., Ragosta, M., Herrera, I.A., and Vennesland, A., 2015. Towards a measure of Resilience. In *5th International Conference on Application and Theory of Automation in Command and Control Systems, ATACCS 2015*, C. Johnson, C. Martinie, P. Palanque, T. Feuerle, F.J. Saez, A. Pasquini, C.G. Rechea, M. Feary, P. van Leeuwen and M. Winckler Eds. Association for Computing Machinery, Inc, 121-128. DOI= http://dx.doi.org/10.1145/2899361.2899374.

[9] Sheffi, Y. and Rice, J.J., 2005. *A Supply Chain View of the Resilient Enterprise*.

[10] Ungar, M., 2018. Systemic resilience: principles and processes for a science of change in contexts of adversity. *Ecology and Society 23*, 4. DOI= http://dx.doi.org/10.5751/ES-10385-230434.

[11] Vallance, S., 2015. An Evaluation of the Waimakariri District Council's Integrated and Community-Based Recovery Framework Following the Canterbury Earthquakes: Implications for Urban Resilience. *Urban Policy and Research 33*, 4, 433-451. DOI= http://dx.doi.org/10.1080/08111146.2014.980401.

[12] Zimmermann, A. and Schmidt, R., 2018. Introduction to Resilient Enterprise Architecture. In *BIR Workshops*

APPENDIX

A. SCOPUS OUTPUT

The SCOPUS search query *TITLE-ABS-KEY (resilien* AND enterprise OR management OR organisation AND architecture) AND ((factor OR indicator)) AND (metric OR measure*) AND (LIMIT-TO(PUBSTAGE, "final")) AND (LIMIT-TO(LANGUAGE, "English"))* resulted in 81 documents.

A majority (50.6%) of the 81 documents are articles. The other documents are conference papers (27.2%), book chapters (11.1%), reviews (6.2%), conference reviews (3.7%) and books (1.2%).

Looking at the number of documents published per year, there is a clear increase visible over the years. All the found documents were published between 2003 and 2019. None were published in 2004 and 2007. In 2003, 2005, 2006 and 2008, 1 document was published each year. In 2009, this number doubled to 2 documents. This increase continued in the years thereafter: 5 in both 2010 and 2011, and 3 in 2012. In 2013, the number of documents increased to 12 after which it decreased in the following years, 7 in 2014 and 8 each year in 2015-2017. In the past year (2018), 13 documents were published and in this year so far (May 2019), this number is 6.

Looking at the countries in which the documents were published, the United States is the leader with 22 documents, followed by the United Kingdom (12) and Germany (6). Greece and Italy both published 5 of the documents while Belgium, Canada, Denmark and Frace all published 4 and China 3 of the documents.

The analysis of the subject area gives quite a scattered image. The documents originate from 19 different subject areas of which Computer Science (19.6%) and Engineering (19.6%) are the largest.

Even more scattered is the analysis of the authors, affiliations and funding sponsors. There seems to be no specific entity which is a major player in this field of research.

Table 1. Criteria assessment based on abstracts

Authors	Title	Year	Context	Cr1	Cr2	Cr3
[No author name available]	13th International Conference on Space Operations, SpaceOps 2014	2014	N/A			
[No author name available]	2013 2nd International Conference on Information Technology and Management Innovation, ICITMI 2013	2013	N/A			
[No author name available]	2013 International Conference on Civil, Architecture and Building Materials, 3rd CEABM 2013	2013	N/A			
Adamy A., Abu Bakar A.H.	Key Criteria for Post-Reconstruction Hospital Building Performance	2019	N/A			
Alexander D.	Political Responses to Emergencies	2014	N/A			
Anthopoulos L., Janssen M., Weerakkody V.	A Unified Smart City Model (USCM) for Smart City conceptualization and benchmarking	2018	N/A			
Anthopoulos L., Janssen M., Weerakkody V.	A Unified Smart City Model (USCM) for smart city conceptualization and benchmarking	2016	N/A			
Bell F.W., Hunt S., Dacosta J., Sharma M., Larocque G.R., Winters J.A., Newmaster S.G.	Effects of silviculture intensity on plant diversity response patterns in young managed northern temperate and boreal forests	2014	N/A			
Bilal M., Oyedele L.O., Akinade O.O., Ajayi S.O., Alaka H.A., Owolabi H.A., Qadir J., Pasha M., Bello S.A.	Big data architecture for construction waste analytics (CWA): A conceptual framework	2016	N/A			
Boskey A.L.	The Biochemistry of Bone: Composition and Organization	2010	N/A			
Byrne R.H., Nguyen T.A., Copp D.A., Chalamala B.R., Gyuk I.	Energy Management and Optimization Methods for Grid Energy Storage Systems	2017	N/A			
Carnwath G.C., Peterson D.W., Nelson C.R.	Effect of crown class and habitat type on climate-growth relationships of ponderosa pine and Douglas-fir	2012	N/A			
Choi S., Chavez A., Torres M., Kwon C., Hwang I.	Trustworthy design architecture: Cyber-physical system	2017	N/A			
Christen B., Dalgaard T.	Buffers for biomass production in temperate European agriculture: A review and synthesis on function, ecosystem services and implementation	2013	N/A			
Ciornei I., Albu M., Sanduleac M., Rodriguez-Diaz E., Guerrero J., Vasquez J.C.	Real-Time optimal scheduling for prosumers resilient to regulatory changes	2018	N/A			
Costan A.	Grid data handling	2013	N/A			

Costan A.	Grid data handling	2011	N/A			
Craig R., Tryfonas T., May J.	A viable systems approach towards cyber situational awareness	2014	N/A			
De Florio V.	Preliminary contributions towards auto-resilience	2013	Computer systems		X	X
De Jonge L.W., Moldrup P., Schjonning P.	Soil infrastructure, interfaces & translocation processes in inner space ("Soil-it-is"): Towards a road map for the constraints and crossroads of soil architecture and biophysical processes	2009	N/A			
de Vrieze P., Xu L.	Resilience analysis of service-oriented collaboration process management systems	2018	Business process mgt.		X	X
Diovu R.C., Agee J.T.	Data aggregation in smart grid AMI network for secure transfer of energy user-consumption data	2018	N/A			
Duc G., Agrama H., Bao S., Berger J., Bourion V., De Ron A.M., Gowda C.L.L., Mikic A., Millot D., Singh K.B., Tullu A., Vandenberg A., Vaz Patto M.C., Warkentin T.D., Zong X.	Breeding Annual Grain Legumes for Sustainable Agriculture: New Methods to Approach Complex Traits and Target New Cultivar Ideotypes	2015	N/A			
Erixon H., Borgström S., Andersson E.	Challenging dichotomies - exploring resilience as an integrative and operative conceptual framework for large-scale urban green structures	2013	N/A			
Erol O., Mansouri M., Sauser B.	A framework for enterprise resilience using service oriented architecture approach	2009	Enterprises		X	
Erol O., Sauser B.J., Mansouri M.	A framework for investigation into extended enterprise resilience	2010	Extended enterprises		X	
Fahey R.T., Fotis A.T., Woods K.D.	Quantifying canopy complexity and effects on productivity and resilience in late-successional hemlock-hardwood forests	2015	N/A			
Famaey J., Wauters T., De Turck F., Dhoedt B., Demeester P.	Network-aware service placement and selection algorithms on large-scale overlay networks	2011	N/A			
Feth P., Adler R., Schneider D.	A Context-Aware, Confidence-Disclosing and Fail-Operational Dynamic Risk Assessment Architecture	2018	N/A			
García Álvarez L., Aylin P., Tian J., King C., Catchpole M., Hassall S., Whittaker-Axon K., Holmes A.	Data linkage between existing healthcare databases to support hospital epidemiology	2011	N/A			
Gard T., Taquet M., Dixit R., Hölzel B.K., de Montjoye Y.-A., Brach N., Salat D.H., Dickerson B.C., Gray J.R., Lazar S.W.	Fluid intelligence and brain functional organization in aging yoga and meditation practitioners	2014	N/A			
Glowacki D.M.	Living and leaving: A social history of regional depopulation in thirteenth-century mesa verde	2015	N/A			
Gomes R.C.S., Tavares Da Costa C., Jr., Silva J.R., Nunes Da Silva P.R.	Automation meta-system applied to smart grid convergence of low voltage distribution legacy grids	2017	N/A			
Hanft A., Burnham M., Goodlin-Jones B., Anders T.F.	Sleep architecture in infants of substance-abusing mothers	2006	N/A			
Harris N., Shealy T., Klotz L.	Choice architecture as away to encourage a whole systems design perspective for more sustainable infrastructure	2017	N/A			
Haßlinger G., Schnitter S., Franzke M.	Load balancing in IP networks in normal operation and with failure resilience	2005	N/A			
Hayashi M., Otani T., Tanaka H., Suzuki M.	Experimental analysis on GMPLS-based photonic switching networks	2003	N/A			
Herrera I.A., Pasquini A., Ragosta M., Vennesland A.	The SCALES framework for identifying and extracting resilience related indicators: Preliminary findings of a go-around case study	2014	Air traffic management		X	X
Hills M.	Socio-technical gambits that destroy cyber security and organisational resilience	2016	N/A			

Kasioumis N., Kotsokalis C., Kranas P., Tsanakas P.	BitTorrent for storage and file transfer in grid environments	2011	N/A			
Kattel G.R., Elkadi H., Meikle H.	Developing a complementary framework for urban ecology	2013	N/A			
Kayes L.J., Anderson P.D., Puettmann K.J.	Vegetation succession among and within structural layers following wildfire in managed forests	2010	N/A			
Lilius R., Salo J., Pérez J.M.T., Metsälä E.M.	Planning and Optimizing Mobile Backhaul for LTE	2015	N/A			
Liu D., Ding Y., Fu Q., Zhao D., Khan M.I., Li T., Faiz M.A.	A novel system of indicators for evaluating system resilience of regional agricultural water resources	2018	N/A			
Martín-Alcón S., Coll L.	Unraveling the relative importance of factors driving post-fire regeneration trajectories in non-serotinous Pinus nigra forests	2016	N/A			
Min I.A., Hant J., Furumoto G., Pfeiffer R.	The portfolio decision support tool (PDST): A software tool for architecture integration and visualization	2015	N/A			
Montibeler P., Farias F., Abelém A.	Topology resilience enhancement for software defined networks	2018	N/A			
Namjoo M.R., Keramati A.	Analysing Causal dependencies of composite service resilience in cloud manufacturing using resource-based theory and DEMATEL method	2018	Cloud manufacturing systems	X	X	X
Ouedraogo K.A., Enjalbert S., Vanderhaegen F.	How to learn from the resilience of Human-Machine Systems?	2013	Human-machine systems	X	X	X
Pal R., Torstensson H.	Aligning critical success factors to organizational design: A study of Swedish textile and clothing firms	2011	N/A			
Paravantis J.A., Kontoulis N., Ballis A., Tsirigotis D., Dourmas V.	A geopolitical review of definitions, dimensions and indicators of energy security	2019	N/A			
Pasquini A., Ragosta M., Herrera I.A., Vennesland A.	Towards a measure of Resilience	2015	Air traffic management	X	X	X
Paz H., Vega-Ramos F., Arreola-Villa F.	Understanding hurricane resistance and resilience in tropical dry forest trees: A functional traits approach	2018	N/A			
Pretzsch H.	Canopy space filling and tree crown morphology in mixed-species stands compared with monocultures	2014	N/A			
Psifidi A., Banos G., Matika O., Desta T.T., Bettridge J., Hume D.A., Dessie T., Christley R., Wigley P., Hanotte O., Kaiser P.	Genome-wide association studies of immune, disease and production traits in indigenous chicken ecotypes	2016	N/A			
Rasouli M.R.	Intelligent process-aware information systems to support agility in disaster relief operations: a survey of emerging approaches	2019	Disaster management		X	
Reznikov N., Chase H., Ben Zvi Y., Tarle V., Singer M., Brumfeld V., Shahar R., Weiner S.	Inter-trabecular angle: A parameter of trabecular bone architecture in the human proximal femur that reveals underlying topological motifs	2016	N/A			
Richardson D.J., Nilsson J., Clarkson W.A.	High power fiber lasers: Current status and future perspectives [Invited]	2010	N/A			
Richnau G., Wiström B., Nielsen A.B., Löf M.	Creation of multi-layered canopy structures in young oak-dominated urban woodlands - The 'ecological approach' revisited	2012	N/A			
Rodríguez-González P.M., Stella J.C., Campelo F., Ferreira M.T., Albuquerque A.	Subsidy or stress? Tree structure and growth in wetland forests along a hydrological gradient in Southern Europe	2010	N/A			
Rohmeyer P., Ben-Zvi T., Lombardi D., Maltz A.	Capability effectiveness testing for architectural resiliency in financial systems	2017	Cybercrime mgt. in finance		X	
Savage G., Franz A., Wasek J.S.	A holacratic socio-Technical system architecture	2016	N/A			
Sennhenn A., Njarui D.M.G., Maass B.L., Whitbread A.M.	Exploring niches for short-season grain legumes in semi-arid eastern Kenya — Coping with the impacts of climate variability	2017	N/A			

Shiomoto K., Inoue I., Oki E.	Multi-layer network operation and management for future carrier backbone networks	2008	N/A			
Shokouhyar S., Seifhashemi S., Siadat H., Ahmadi M.M.	Implementing a fuzzy expert system for ensuring information technology supply chain	2019	N/A			
Sim J., Loh G.H., Sridharan V., O'Connor M.	Resilient die-stacked DRAM caches	2013	N/A			
Sousa-Silva R., Verheyen K., Ponette Q., Bay E., Sioen G., Titeux H., Van de Peer T., Van Meerbeek K., Muys B.	Tree diversity mitigates defoliation after a drought-induced tipping point	2018	N/A			
Suweis S., Simini F., Banavar J.R., Maritan A.	Emergence of structural and dynamical properties of ecological mutualistic networks	2013	N/A			
Tan L., Chen Z., Song S.L.	Scalable energy efficiency with resilience for high performance computing systems: A quantitative methodology	2015	N/A			
Thrush S.F., Hewitt J.E., Lohrer A.M.	Interaction networks in coastal soft-sediments highlight the potential for change in ecological resilience	2012	N/A			
Toffetti G., Brunner S., Blöchlinger M., Spillner J., Bohnert T.M.	Self-managing cloud-native applications: Design, implementation, and experience	2017	Cloud applications		X	X
Ulltveit-Moe N., Gjøsæter T., Assev S.M., Køien G.M., Oleshchuk V.	Privacy handling for critical information infrastructures	2013	N/A			
Ungar M.	Systemic resilience: principles and processes for a science of change in contexts of adversity	2018	Systems		X	
Vallance S.	An Evaluation of the Waimakariri District Council's Integrated and Community-Based Recovery Framework Following the Canterbury Earthquakes: Implications for Urban Resilience	2015	Disaster management		X	
Vallero A., Savino A., Chatzidimitriou A., Kaliorakis M., Kooli M., Riera M., Anglada M., Di Natale G., Bosio A., Canal R., Gonzalez A., Gizopoulos D., Mariani R., Di Carlo S.	SyRA: Early system reliability analysis for cross-layer soft errors resilience in memory arrays of microprocessor systems	2019	N/A			
Varshney R.K., Tuberosa R., Tardieu F.	Progress in understanding drought tolerance: From alleles to cropping systems	2018	N/A			
Vega A., Bose P., Buyuktosunoglu A., DeMara R.F.	Reliable and power-aware architectures: Fundamentals and modeling	2016	N/A			
Wang Z., Yang H., Wang D., Zhao Z.	Spatial distribution and growth association of regeneration in gaps of Chinese pine (Pinus tabuliformis Carr.) plantation in northern China	2019	N/A			
Wied M., Oehmen J., Welo T.	Resilient design properties of a driverless transport system	2018	Autonomous public transport		X	
Wig G.S.	Segregated Systems of Human Brain Networks	2017	N/A			
Williams P., Hargreaves C.	UK eLoran - Initial operational capability at the port of dover	2013	N/A			