Case study application of a strategic complexity management framework for complex industrial systems

Lucas Freund[1,*], Salah Al-Majeed[1] Alan Millard[1]
University of Lincoln[1]
lucas.freund@hotmail.de

Abstract: *A strategic decision-making tool to generate holistic strategic complexity management strategies for complex engineered systems (SCM) is applied to a real-world case of an industrial manufacturing system at a European health & beauty manufacturer. The case study has the the goal to test and discuss the practical applicability of the SCM framework. As a first step, the SCM basic structure, the applied complexity dimensions in the form of structural, dynamic, and environmental complexity are demonstrated. In a second step, the framework's strategic capabilities are theoretically demonstrated based on a set of generic norm strategies. In a third step the results of the SCM application on the described case is described, results and learnings are identified and discussed. As a final step, a short outlook for further research is provided..*

Keywords: *COMPLEXITY, STRATEGIC MANAGEMENT, INDUSTRY 4.0, CASE STUDY*

1.Introduction

Today decision-makers face surging increases in volatility, uncertainty and over-all business complexity leading up to more unstable and unpredictable business environments. Leaders and decision-makers are confronted with the so-called VUCA-world, an acronym standing for (i) volatility (dynamic and intense chang-es), uncertainty (lack of predictability), complexity (interconnection of parts which is sometimes overwhelmingly difficult to process), and ambiguity (unclear relationships).[1,2] Even though individual VUCA aspects on their own can al-ready lead to overwhelming challenges, a combination of VUCA aspects or the presence of all four combined can lead to complex business problems that are nearly unsolvable for decision-makers.[3,4] The components of the VUCA-world thus represent the main four challenges for doing sustainable business and de-signing strategy in the modern business world. They are consequently adopted by business leaders and decision-makers to describe and address the rapid changes of the business environment and to capture and benefit of overcoming challenges and newly arising opportunity. [1,2,3] In the context of engineered systems, the implications of the VUCA-world for business and strategy can be applied to the rise of cyber-physical systems (CPS). CPS represent new and complex systems or system environments, in the form of cyber-physical systems of systems (CPSS) that combine the potentials of physical artifacts, humans and engineered systems due to integrated computational and physical capabilities. CPS are established to produce a global intelligent behavior featuring autonomy, self-control and self-optimization and are expected to be a decisive driving force for advances in dif-ferent areas in manufacturing, opening up new areas of innovation. [5,6,7,8,9,10,11] In contrast to the potential of CPS for manufacturing it is well understood that current and more traditional manufacturing and industrial sys-tems are already stretching the limits in terms of the development of cost-efficient and trustworthy systems. This urgent matter is additionally amplified by the circumstance that current CPS system design already is unable to support the level of complexity, scalability, security, safety, interoperability, and flexible design and operation that will be required to meet future needs decision. [3] The line of argument makes visible that it is now imperative for industry decision-makers to obtain practical methods and tools of strategic planning addressing the management of complex industrial systems and thus aiming to solve the chal-lenges of the volatility, uncertainty, complexity, and ambiguity.[4] One option to achieve this are holistic strategic management frameworks in the form of strate-gic management tools and techniques (SMTT) dedicated to strategic complexity management. SMTTs are proven tools to positively influence organizational per-formance, assist strategic managers in decision making, can be applied to all stages of the decision-making process, and are consistently applied to many di-verse engineering disciplines, like industrial engineering, artificial intelligence, systems science, or the management of information systems. [12,13,14,15]

Motivation & Novelty

The main motivation of this paper is to contribute to the topic of strategic com-plexity management for engineered systems by showcasing and discussing the application of a Strategic Complexity Management framework (SCM) for the complexity analysis of a manual assembly line in a world-market leading Euro-pean beauty & health manufacturer. The company can be defined as a small/medium enterprise (SME). The SCM has the explicit goal to serve decision-makers and managers of manufacturing companies, like the described SME, as an SMTT in the decision-making process for current and future complex industrial systems. The SCM builds upon the previous findings and propositions of Freund & Al-Majeed in the areas of theoretical modelling industrial IoT system complex-ity, as well as CPS and CPSS complexity. [16,17] It is also necessary to mention, that this paper is to be considered as part of the theoretical and practice-based foundation for current and future complexity management research for industrial systems based on the application of the SCM an real-world case in collaboration with European industry partners. This paper now consists out of the following steps (i) description of the SCM framework (ii) case study approach, case de-scription and results (iii) derived key-learnings (iv) discussion and outlook.

2. Strategic Complexity Management Framework

The SCM framework is now introduced. Figure 1 now illustrates the basic structure of the SCM framework.

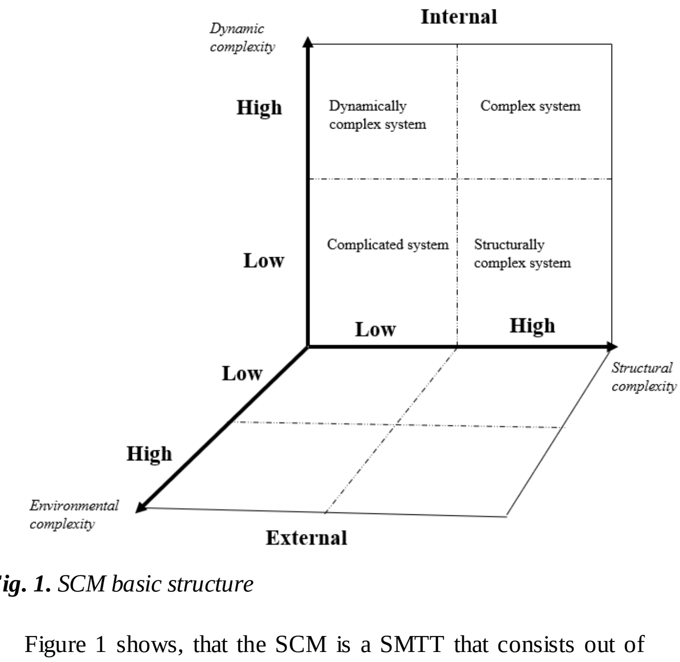

Fig. 1. *SCM basic structure*

Figure 1 shows, that the SCM is a SMTT that consists out of two generic 2x2 ma-trixes, resulting in an 8-quadrant matrix, with two perspectives of analysis (inter-nal, external) in three complexity dimensions where structural (S) and dynamic (D) complexity represent the internal perspective and environmental (E) complexity represents the external perspective of strategic management. In this anal-ysis The SCM now allows to qualify each complexity dimensions in a scale be-tween HIGH and LOW. The resulting intersections of the qualifications result in a system internal and system external classification.

Applied Conception of Complexity

As already shown by Figure 1 three different dimensions of complexity are utilized by the SCM. Figure 2 illustrates the applied conception of complexity for this paper.

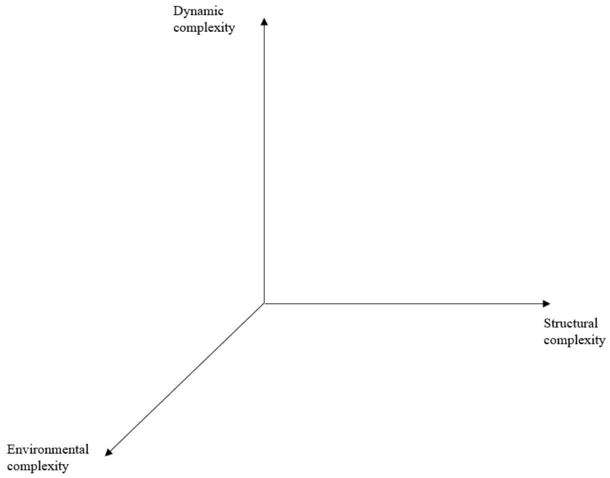

Fig. 2. *Applied conception of complexity*

Table 1 now describes the three dimensions in more detail.

Table 1. Complexity dimensions

Dimension	Description
Environmental (E)	Three main environments can be identified: *Task environment* (all aspects relevant to setting goals and achieving them), *technical environment* (location where companies produce their products and services), *institutional environment* (formal rules and beliefs of the company). [18,19,20, 21,22
Structural (S)	The static, time-independent architectural layout of a manufacturing process represented by *machines*, operations, their connections via links, and their level of interconnectedness. [23,24,25]
Dynamic (D)	*Information* in a system is regarded in the context of the SCM as a measure of entropy and disorder in the form of uncertainty in the system. A low entropy value implies low uncertainty and vice versa. The higher the disorder, the higher the entropy. If the system is well ordered, it is easy to understand, predict its behavior, and to describe and communicate it. [11,16,23,26,27]

After introducing the applied three complexity dimensions, the next sections provide further insight into how the SCM can be analytically applied. This also shows, that the SCM is inspired by the structure and function of proven, valued and practice based SMTTs like the SWOT or BCG matrix. [21,22]

It can be stated, that the greater the complexity of the system, the greater the amount of information that must be processed between decision-makers during its execution in every complexity dimension. [28] This shows that any strategic analysis of the applied final complexity conception can only be valuable to the decision-maker if the analysis holistically integrates all mentioned dimensions of complexity in a balanced, coherent way. This allows the decision-maker to assess the system and its behavior as a whole and to identify as well as investigate individual drivers that influence system performance. [12,21,22,28] The challenge in designing a SMTT for complex engineered systems therefore lies, especially for systems of unprecedented complexity like CPS and CPSS, in designing a holistic SCMTT framework to study complexity which is at the same time applicable for practice-based use.

SMTT Example: SWOT & BCG Matrix

To illustrate the functioning of a SMTT, the SMTT “SWOT analysis” in the form of the SWOT strategic matrix is now described and illustrated. SWOT analysis was first designed and introduced in 1960 by Stanford´s research institute and since 1975 was widely used as an analytical framework for developing company strategies and it is still applied in current research applications. [21] The SWOT matrix properly analyzes the internal strengths and weaknesses as well as external threats and opportunities to guide the future expected strategies. This matrix, as shown in Figure 3, is a useful tool for strategic planning of strategic management and a fundamental basis for identifying conditions and planning future methods which are necessary for strategic observation.

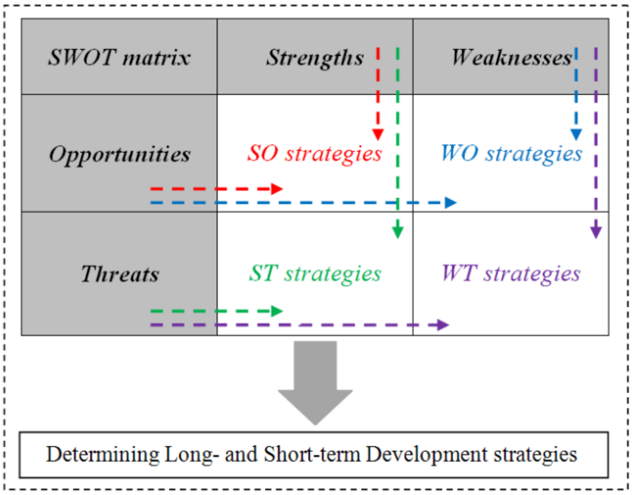

Fig. 3. *SWOT Matrix*

Figure 3 shows, that in the SWOT analysis, the internal and external factors are evaluated first, which is called the input stage, and the information required for devising strategies is determined. During the second stage, which is called the comparison stage, all the possible strategies are considered through developing a SWOT matrix. The objective of this matrix is to determine all applicable strategies and the best strategy is not sought at this stage. Strategists could use this matrix to create and introduce four kinds of generic norm strategies (SO, WO, ST, and WT strategies). [22] Another prominent example for a matrix based SMTTs is the BCG Matrix, which is now illustrated in Figure 4.

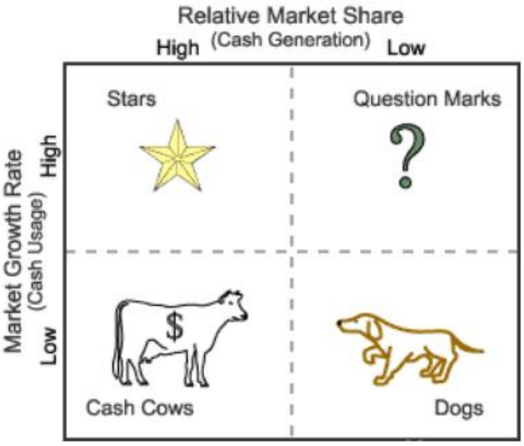

Fig. 4. *BCG Matrix*

Both provided examples share a generic matrix format with a simple two-dimensional analysis, which both reflect the company internal and external view. Both examples allow to effectively and categorize decision-problems and to deduct first norm strategies as an answer in a holistic way. This is supported by the research of Afonina who shows that in general managers prefer to use holistic tools and techniques. [12] After introducing the theoretical foundation and inspiration for the SCM framework the SCM analysis process can now be introduced and described in detail.

Internal Analysis & Qualification

Initially, the internal complexity of the analyzed system is determined by qualifying the dimensions of structural and dynamic complexity to achieve the internal system classification through a HIGH / LOW qualification combination of the dimensions of structural and dynamic complexity. Table 2 now summarizes all internal system classifications.

Table 2. Internal classification

Classification	Qualification combination (S / D)	Description
Complicated system	Low/Low	Non-complex, well-understood system
Complex system	High/High	Non-linear, partially random system
Structurally complex	High / Low	Structure as main source of complexity
Dynamically complex	Low/High	Information as main source of complexity

Table 2 shows, that the internal classification of SCM allows to classify in four different classifications in the range of a complicated to complex system through the four related HIGH / LOW qualification combinations. Consequently, the goal of the internal SCM classification is to achieve the specific system classification which is then extended by the external system classification for the final system classification. This process is described in the next section.

External Analysis & Qualification

The resulting internal system classification, as shown in Table 2, is now applied to the LOW/HIGH qualification of the system external dimension. For example, a LOW/HIGH dynamically complex system is combined with a HIGH environmental complexity and results in a complex system. Figure 5 illustrates all possible combinations.

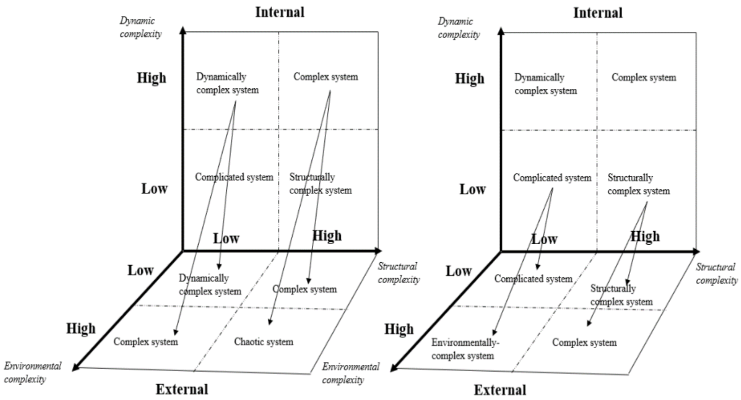

Fig. 5. *External system classification*

Overall, it can be stated that a LOW external qualification generally means in the context of the SCM framework that the external environment of the system is clearly definable and is not contributing to uncertainty while a HIGH external qualification means that the external environment of the system is a major source of uncertainty and is likely to lead to a system of higher complexity classification, for example creating a chaotic system out of a complex system ((S/D/E);(HIGH/HIGH/HIGH)). [18,20,24,28]

SCM Norm Strategies

After achieving system qualification and classification a first set of norm strategies in the form of identify, manage, and avoid can be applied.[28] The strategy *manage* includes These norm strategies are put into the SCM context as described in Figure 6.

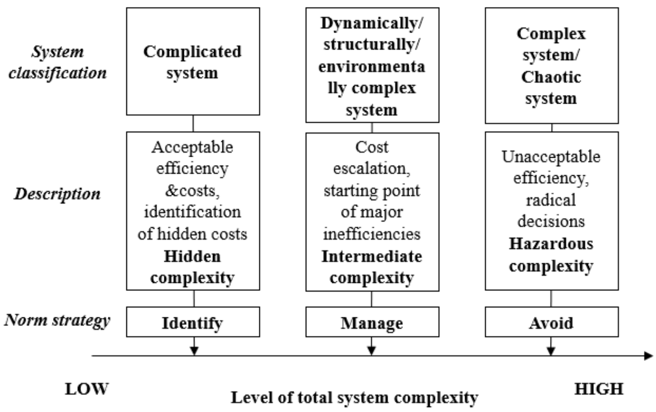

Fig. 6. *SCM norm strategies*

Figure 7 now summarizes the complete SCM process.

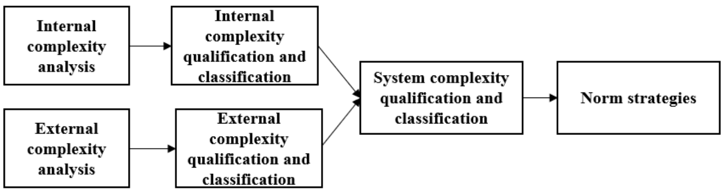

Fig. 7. *Complete SCM process*

After presenting the SCM framework, the applied case study method for this paper is now introduced and described in detail.

3. Case Study Design

The following table gives an overview about the relevant elements of case-study based research for this paper, their description, and the transfer of the research to the SCM. [29] Table 3 now illustrates the applied case study design.

Table 3. Case study design

Element	Description (Case specific)
Unit of analysis	Application of SCM on industrial manufacturing system of two different companies in Austria and Germany.
Selection criterion	Industrial manufacturing system poses a complex decision-making problem to senior decision-makers
Data collection process	Companies provide research team with a set of documents primary information source
Collecting the data (forming the database)	Information sources include: I. Project documents (Factory layouts) II. Project reports, including quarterly reports, midterm review III. Calculations IV. Facility assessment reports V. Maintenance reports and others (videos etc.)
Analyzing the data	Document review & analysis process + application of SCM
Interpretation of data / SCM analysis	Interpretation of results of SCM with the aim to generate norm strategy for individual case

The chosen research design allows to achieve the following principles of data collection to contribute to the validity and reliability of the study as well as rigor and thoroughness in the case study process: (i) multiple sources of evidence in the form multiple document types (ii) database creation (iii) maintaining a transparent chain of evidence in the SCM analysis process. [30,31] In the next section the document review process for the generated database is described.

4. Case Study: Manual Assembly Line

The SCM has been utilized for complexity analysis in the planning process of a new production system at an international health & beauty SME. A central motivation and goal of the SME to use SCM analysis was to support senior management in development and planning of the mentioned production line. The goal of the research team was to apply and test the SCM in a real-world practice-based environment. To achieve this, the company provided all existing documentation as the data basis for SCM analysis.

.

SCM Analysis

Through the application of the SCM on the database the production system is classified as a dynamically complex system with the qualification ((S/D/E); (LOW/HIGH/LOW)).

Norm Strategy

As shown in Figure 9, the resulting norm strategy for the system is MANAGE, with intermediate system complexity and potential starting points of cost-escalation and major inefficiencies.

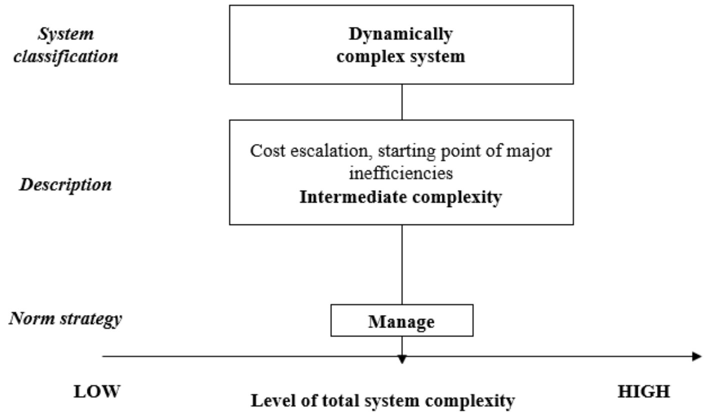

Fig. 8. *Norm strategy for manual assembly line*

Nnorm strategy implementation

The following two measures were defined to allow norm strategy implementation into practice. The following measures were determined: (i) Outsourcing of non-essential production steps to external suppliers (ii) Identification of points of cost escalation through cost scenario analysis of insourcing / outsourcing combinations of non-essential production steps.

Learnings

The following learnings can be obtained: i) manufacturers were able to provide the research team with sufficient documents of significance and information richness to allow meaningful and valid analysis and results (ii) the research team was able to apply the SCM on the case without having to depart from the framework structure and functioning or breaking the coherence of the SCM (iii) all received documents were successfully applied to SCM dimensions (iv) the SCM was capable to generate valid results in the form of norm strategies for all analyzed cases (v) the generated SCM norm strategies were successfully implemented into practice.

Discussion of Results

The application and results generated by the SCM and the learnings obtained in the analyzed case indicate that holistic practice-based SMTTs for strategic complexity management, like the SCM, can provide meaningful and helpful assistance to decision-makers in the manufacturing industry in the process of strategy development when dealing with complex problems concerning volatility, uncertainty, complexity, and ambiguity. Due to the system type of the cases analyzed (manual assembly line), even though still complex for the decision-makers of the company, it remains unclear if the SCM also provide useful strategic implications in the context of hyper-complex, less traditional and generally less understood systems like CPS and CPSS. Such systems might be documented in more unorthodox or non-standard ways and document analysis might be less efficient and effective for the SCM. In summary, the results of the presented case study show that SMTTs like the SCM can be regarded as a highly relevant holistic and practice-based approaches for decision-makers to strategically solve problems of complexity for industrial engineered systems.

5. Conclusion

A strategic complexity framework in the form of the SCM is introduced and functions as a practice based SMTT for complexity analysis of current and future complex industrial systems. The dimensions of the model in the form of structural, dynamic, and environmental complexity are briefly introduced and described. The core capabilities in the form of system qualification, classification, and norm strategies of the SCM framework are theoretically demonstrated. The SCM is applied for the strategic complexity management analysis of a production system in a European beauty & health SME with the goal to support senior management decision-making. The analyzed case, the chosen case study approach, the case study results and resulting learnings are described and discussed. It is shown by the results of the case study, that SMTTs like the SCM can provide valuable strategic support for decision-makers in the manufacturing industries. There are now many open directions for future work. First, conducting more real-world case study applications and cross-case analysis would be helpful to define the practical value of the norm strategies more clearly. Second, applying the SCM on more complex systems. Finally, longitudinal case applications of the SCM framework would help in understanding the long-term value of results.

6. References

[1] N. Bennet and G. Lemoine, "What a difference a word makes: Understanding threats to performance in a VUCA world.", Harvard Business Review 2014, 2014, pp.1-7

[2] C. Potsangbam, "Adaptive Performance in VUCA era – where is research going?", International Journal of Management Volume 8 Issue 6, 2017, pp. 99-108

[3] T. Krawczynksa-Zaucha, "A new paradigm of management and leadership in the VUCA world", Scientific papers of Silesian university of technology: Organization and Management Series No. 141, 2019, pp. 222-230

[4] Millar et.al, "Management Innovation in a VUCA World", California Management Review Volume 1 Issue 10, 2018

[5] M. Törngren and U. Sellgren, "Complexity Challenges in Development of Cyber-Physical Systems", Springer International Publishing AG, part of Springer Nature 2018, 2018, pp. 478-503.

[6] Gaham et. al., "Human-in-the-Loop Cyber-Physical Production Systems [Contol HiLCP2sC) A Multi-objective interactive framework Proposal", Service Orientation in Holonic and Multi-agent Manufacturing, Springer-Verlag Berlin Heidelberg, 2013, pp.315-325

[7] I. Horvarth and B. Gerritsen, "Cyber physical systems: concepts, technologies and implementations", Proceedings of TMCE 2012, 2012 pp.19-22.R. Nicole, "Title of paper with only first word capitalized," J. Name Stand. Abbrev., in press.

[8] M. Törngren and P. Grogan, "How to Deal with the Complexity of Future Cyber-Physical Systems?", Designs 2018 2,40, 2018, pp. 1-16

[9] A. McAfee and E. Brynjolfsson, "The second machine age", W.W. Norton & Company, New York, 2014, pp.13-24; pp.26-34.

[10] Garcia et. al, "A human-in-the-loop cyber-physical system for collaborative assembly in smart manufacturing", Procedia CIRP Volume 81, 2019, pp.600-605.

[11] E. Aslaksen, "Designing complex systems", CRS Press, 2019, pp.75-85

[12] A. Afonina, "Strategic Management Tools and Techniques and Organizational Performance: Findings from the Czech Republic", Journal of Competitiveness Volume 7 Issue 3, 2015

[13] Qehaja et. al, "Strategic Management Tools and Techniques Usage: A Qualitative Review", Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis Volume 65 Issue 2, 2017, pp. 585-600

[14] Nouri et. al, " Analyzing the use of strategic management tools and techniques between Iranian firms", Academy of strategic management journal Volume 16 Issue 1, 2017

[15] Qehaja et.al, "Strategic Management Tools and Techniques: A Comparative Analysis of Empirical Studies", Croatian Economic Survey Volume 19 Issue 3, 2017, pp. 67-99

[16] L. Freund and S. Al-Majeed, "Cyber-Physical Systems as Sources of Dynamic Complexity in Cyber-Physical-Systems of Systems," 2020 International Conference on Innovation and Intelligence for Informatics, Computing and Technologies (3ICT), Sakheer, Bahrain, 2020, pp. 1-5, doi: 10.1109/3ICT51146.2020.9312015

[17] L. Freund and S. Al-Majeed, "Modelling Industrial IoT System Complexity," 2020 International Conference on Innovation and Intelligence for Informatics, Computing and Technologies (3ICT), Sakheer, Bahrain, 2020, pp. 1-5, doi: 10.1109/3ICT51146.2020.9311942.

[18] S. Jofre, "Strategic Management: The theory and practice of strategy in (business) organizations", DTUManagement. DTU Management 2011, No. 1, 2020

[19] T. Sammut-Bonnici, "Strategic management", Wiley Encyclopedia of Management -Volume 12 Strategic management, Wiley, 2015

[20] Ghani et. al., "Critical Internal and External Factors that Affect Firms Strategic Planning." International Research Journal of Finance and Economics, 2020

[21] Fahrhangi et. al, "Development SWOT Matrix for Strategic Planning in Media Organizations", International Journal of Business and Commerce Volume 1 Number 5, 2021, pp. 1-12

[22] H. Mohajan., "An Analysis on BCG Growth Sharing Matrix", Noble International Journal of Business and Management Research Volume 2 Number 1, 2018, pp.1-6

[23] D. Mourtzis., "Modelling and quantification of industry 4.0 manufacturing complexity based on information theory: a robotics case study", International Journal of Production Research, 2019 p.3

[24] I. Garbie, "Concepts and measurements of industrial complexity: a state-of-the-art survey", Int. J. Industrial and Systems Engineering, Vol. 12, No. 1,2012, pp.43-55

[25] A. Wortmann, "Modelling and simulation of industrial systems", De Lier: Academisch Boeken Centrum, 1991

[26] A. Johansson, "Entropy and the cost of complexity in industrial production", Exergy, an International Journal Volume 2, 2002, pp.295-299

[27] H. Li., "Information Efficiency of Communications for Networked Control in Cyber-Physical Systems: When Carnot Meets Shannon".2016 IEEE 55th Conference on Decision and Control (CDC), 2016, pp. 12-14.

[28] B.Jamshidnezhad, "Internal versus external complexity: how organizations react", 21st International Congress on Modelling and Simulation, 2015, pp.71-77

[29] Harrison et.al, "Case Study Research: Foundations and Methodological Orientations". Forum Qualitative Sozialforschung / Forum: Qualitative Social Research Volume 18 Issue. 1, 2017

[30] Z. Kaman and Z. Othman, "Validity, Reliability and Triangulation in Case Study Method: An Experience", Qualitative Research Conference (QRC) 2016, 2016, pp. 24-26