Journal of Mechatronics and Robotics

Original Research Paper

Analysis of Mechatronics Degree Evaluation Models

Jean Bosco Samon and Brice Landry Tekam Guessom

Department of Mechanical Engineering, University of Ngaoundere, Cameroon

Article history
Received: 14-04-2022
Revised: 03-07-2022
Accepted: 05-07-2022

Corresponding Author:
Jean Bosco Samon
Department of Mechanical Engineering, University of Ngaoundere, Cameroon
Email: jboscosamon@gmail.com

Abstract: A mechatronic system is an intelligent product that is usually very complex and deserves to be characterized. The complexity comes from the number of integration of functions in a single product. Mechatronizability, which is the ability of the degree of mechatronics of a system, is a remarkable characteristic for designers to decide the level of complexity at the design stage of multifunctional products. The concern is therefore to estimate the multifunctional degree of a mechatronic product. After the description and analysis of a mechatronic system, two methodological approaches are proposed based on three metric models: the functional integration indicator which reflects the degree of collaboration of components in the realization of functions of a product. The functional complexity indicator which reflects the level of interpenetration between the elements belonging to the different domains existing in each of the product functions. The functional dematerialization indicator which measures the degree of integration of electronic "E", computer "I" and automatic "A" areas in a product. These indicators have been applied to a hydraulic pump. The designer will now have to know the mechatronizability of a product to decide on its degree of intelligence.

Keywords: Metrics, Product Design, Mechatronic Evaluation, Mechatronizability, Functional Analysis

Introduction

The birth of mechatronics can be considered a revolution for the industrial world. The use of these systems quickly became widespread and now influences almost all sectors of industry today. The term mechatronics responds to the need to define an industrial activity for the development of hybrid products that integrate, in an advanced and hitherto unseen way, technologies that have been used separately until now. It defines design engineering as aimed at the synergistic integration of mechanics, electronics, automation, and computer science in the design and manufacture of a product to increase and/or optimize its functionality (Leonida, 2017). Mechatronics is also promoted as a technology that reduces costs and increases the added value of the product by increasing its functionality.

In the light of the literature, two currents of thought are observed.

The mechatronics trend that aims to design and manufacture integrated products has continued to develop to the point that nowadays the scope of mechatronics covers many of our everyday or industrial objects and includes for example the development of the Internet of Things (Ajah *et al.*, 2015). The Internet of Things has been identified as a very high-growth sector very shortly. Indeed, these commonly used products offer a very wide spectrum of functional services. Mechatronics, on the other hand, is studied from several perspectives: Ontology development aspects for collaborative engineering are studied by (Damjanović *et al.*, 2007) and also touch on transdisciplinary education (Pop and Măties, 2010), emphasizing the need for professional training throughout a mechatronics pathway and specific problem-solving methods as levers for success (Pop *et al.* 2010). Connected objects, (Ajah *et al.*, 2015) that integrate into physical systems also present an important part of the research as well as the reliability of mechatronic systems (Demri, 2009).

Mechatronics is therefore essential to the industry of the future and consequently to the factory of the future since without mechatronics there would be no intelligence or connectivity between machines. Moreover, companies both supply and use mechatronic technology solutions. It is, therefore, appropriate to study how companies that produce and market these products are organized. It is still necessary to find a population of companies that allows concrete and precise targeting (Fradi *et al.*, 2021).

Yet another trend concerns metrics for modeling mechatronic design processes (Bonjour *et al.*, 2009; Bonjour and Micaelli, 2009), facilitating the evaluation of

DOI: 10.3844/jmrsp.2022.57.64

architectures in systems engineering (Lo, 2013), implementing agile processes in the preliminary design phases (Bricogne-Cuignières, 2015), or for instrumenting the profession of mechatronic system architect (Turki, 2008; Bonjour, 2008; Bonjour *et al*., 2009; Bonjour *et al*., 2013) and (Warniez, 2015). The mechatronic process is related to the life cycle of mechatronic products. It is a mechatronic process that allows achieving higher performance than traditional solutions, realizing new functionalities, and making mechatronic products more compact. This process requires the implementation of an interdisciplinary cooperative approach. Increasing and optimizing the functionality of mechatronic products requires the cooperation of several disciplines and the collaborative aspect is a necessary condition. Namely, it is necessary to make specialists from several different fields work together.

Considering the economic growth forecasts in the field of Mechatronics, many manufacturing Small and Medium Enterprises (SMEs) and Small and Medium Industries (SMIs) will have to develop industrial activities in the field of Mechatronics engineering in the very short term. These companies will have to be able to meet the needs for advanced components. They will therefore be led to adopt an organization and processes that will enable them to produce mechatronic products to be integrated into the economic dynamics caused by the development of these highly technologically integrated systems. If the large groups and most of the companies of intermediate size have already set up an organization and specific processes which allowed the realization of emblematic mechatronic products with great diffusion, this tendency is not generalized for the great majority of the SMEs. Moreover, the processes of large companies are not necessarily directly transposable to small companies due to many differences in organization and availability of resources.

This study is conducted from the perspective of providing support tools to SMEs considering to evolve from a single-domain sectorial activity to a measurable multi-domain mechatronics activity. It is therefore useful to look for a model to evaluate the degree of mechatronics of a product to delimit the functional capability of the product to be able to design an adequate production unit.

Physical integration defines the integration of mechanical and electronic supports. In a broader sense, it indicates that the functions of a mechatronic product result from the combination of components of multi-domain technologies. Functional integration defines the addition of sensing, communication, information processing, and feedback functions to the basic mechanical functions. To qualify a mechatronic product, the standards necessarily lead us to take into account first the functions of the product. The method proposed here is therefore based on the functional definition of the product. The quantification of the physical or functional integration level requires them to identify and list the components and their technological domain used to satisfy the identified functions of the product. This means evaluating the functional flows for each component. Once these flows are established, it is then possible to evaluate different indicators quantifying the level of mechatronizability of the product.

This research aims to propose metrics for the evaluation of technological solutions adopted to meet the functional needs of mechatronic products. This evaluation should help companies to define the level of functional integration by identifying the particular characteristics of organizations that can design complex products and that belong a priori to a specific category: "Mechatronic" companies. Therefore, one of the major problems that this multidisciplinarity of mechatronic systems poses to experts is: "The evaluation of mechatronics at the design stage". To answer this problem, we have considered a method of evaluating the degree of mechatronics which is the use of metrics. This article reviews the state of the art by analyzing the evaluation models of the degree of mechatronics based on the metrics studied by two main authors: Tabourot and Leonida. An application of each model will allow making a critical synthesis to propose later an optimal metric of the mechatronizability of a product.

Materials and Methods

Presentation of the Metrics

Generally speaking, authors agree that a metric makes it possible to measure and therefore compare several things. In the field of design, it is often a question of quantitatively evaluating several solutions through various criteria, which will be combined, possibly with certain weightings, to obtain an overall value representative of what we are seeking to evaluate (objective) (Leonida, 2017). Thus, a metric is defined by "a combination (mathematical functions) of criteria or indicators involving one or more directly measurable parameters. These mathematical functions can be simple such as sum, subtraction, multiplication, division, but also polynomial, logarithmic, exponential functions, or more complex equations".

Metrics Proposed by Leonida (2017)

The metric models for assessing the degree of mechatronics proposed by Leonida (2017) are given below:

a. The Functional Integration Indicator

Abbreviated as *IntegMax*, it measures the degree of collaboration of components in the realization of functions of a product. It is given by the equation below:

DOI: 10.3844/jmrsp.2022.57.64

$$IntegMax = \frac{\frac{\sum_{fonctions} NCF}{NF} - 1}{NC - 1} \quad (1)$$

Number of Components (NC), Number of Functions (NF), Number of Components per Function (NCF).

If IntegMax = 1: Each component of the system contributes to the realization of all the functions fulfilled by the product (very high integration). The system becomes a single component in its own right. On the other hand, a value of zero (0) for IntegMax shows that the system is modular because each function is performed by a single component of the system:

b. The functional dematerialization indicator

Abbreviated *Dem Max*, this indicator measures the degree of integration of electronic "E", computer "I", and automatic "A" domains in a product. This indicator reflects the level of communication, intelligence, autonomy, and performance gained by a mechatronic product. It is given by the expression:

$$DemMax = \frac{NF_{EIA}}{NFP} \quad (2)$$

NF_{EIA}: Number of Functions related to "E", "I", "A
NFP: Number of Functions of the Product

The closer it is to 1, the more electronic, computer, and automatic domains are present in the equipment, which demonstrates a high degree of intelligence:

c. The functional complexity indicator

Abbreviated as ComplexiMax, it reflects the level of interpenetration between the elements belonging to the different domains existing in each of the product's functions. It is given by the equation below:

$$ComplexiMax = \frac{1}{28} \times \frac{\sum_i NcoFi}{NF} \quad (3)$$

NcoFi: Number of couplings per function *i*
NF: Number of functions

If *ComplexiMax* = 0: The product is mono-domain and therefore not mechatronic. On the other hand, value 1 shows that the 8 domains (mechanical, electronic, command-automatic control, computer, hydraulic-pneumatic, optical, magnetic, and thermal) are present in all functions of the product, the product is strongly mechatronic.

Metrics Proposed by Tabourot and Balland (2017)

The metric models for assessing the degree of Mechatronics proposed by Tabourot are given below:

a. The Functional Integration Indicator

It is given by the equation below:

$$IntegMax = \frac{\frac{\sum_{fonctions} NMF}{NF} - 1}{NM - 1} \quad (4)$$

NMF: Number of modules per function
NM: Number of modules

If *IntegMax* = 1: Each functional module of the system contributes to the realization of all the functions fulfilled by the product (very high integration), on the other hand, the value zero (0) shows that the system is modular because each function is realized by only one functional Module of the system. The method of defining the number of system module can be retrieved at (Ericsson and Erixon, 1999) and (Djami *et al*., 2020).

b. The functional dematerialization indicator

It is the sum of four intermediate indicators which are the indicator relating to the electronic, computer, and automatic functions DemMaxEIA, the information indicator DemMaxinfo, the diagnostic indicator DemMaxdiag and the intervention indicator DemMaxinterv and are given by the following equations:

$$DemMaxEIA = \frac{NF_{EIA}}{NFP} \quad (5)$$

$$DemMaxinfo = \frac{NFIf}{NFEIA} \quad (6)$$

$$DemMaxdiag = \frac{NF_d}{NF_{EIA}} \quad (7)$$

$$DemMaxintev = \frac{NFI_t}{NF_{EIA}} \quad (8)$$

$$DemMax = \sum_{i=1}^{i=4} \lambda_i \, DemMax_i \quad (9)$$

λi = the sum of the weights; i = EIA, If, d or It functions:

NF_{EIA}: Number of functions related to the field of electronics, automation, and informatics
NF_{If}: Number of information functions

NF_{It}: Number of intervention functions
NF_d: Number of diagnostic functions

The coefficients λi define the weights of the indicators. The sum of these must be equal to 1. The closer the indicator $DemMax$ is to 1, the more dematerialization areas including electronics, IT, and automation are present in the product:

c. The functional complexity indicator

This indicator proposed by Leonida (2017) is the same as the one proposed by Tabourot and Balland (2017).

Results and Discussion

Application of the Metrics

In the framework of this analysis, the equipment used will be a hydraulic pump presented in Fig. 1 below.

To calculate the metrics, we must first follow the procedure illustrated in Fig. 2 after having described the product beforehand.

Figure 3 below shows us the Octopus diagram which illustrates the environment of the PW hydraulic pump with two functions retained for the pump. These are F1 (Supply the hydraulic motor to move a vehicle) and F2 (Attach to the thermal engine)

After defining the functional environment of the PW hydraulic pump, Fig. 4 illustrates the functional flow chart of the product based on a rather trivial decomposition of the product.

The functional flow elements have been grouped into two modules because a pump is made of a fixed and rotating assembly.

As the modules and functions have already been defined, we are going to build the incidence matrix between modules and functions (Table 1).

Application of the Metrics Proposed by Tabourot and Balland (2017)

The data for an application on the hydraulic pump of the metrics proposed by Tabourot and Balland (2017) has already been done in the Table 1 and the results obtained are the following: Functional integration indicator IntegMax = ((3/2)-1)/(2-1) = 0.50 shows that there is a collaboration between the functional modules and Functional dematerialization indicator DemMax = 0.38 (DemMaxEIA = 0.5; DemMaxinfo = 1; DemMaxdiag = 0; DemMaxinterv = 0) shows a rather low degree of intelligence of the hydraulic pump.

Functional complexity indicator ComplexiMax = 0.02. This rather low number corresponds well to the studied product which presents very few couplings.

Application of the Metrics Proposed by Granon (2017)

Functional Integration Indicator

We list the functions performed by the product and the list of components with their function scores (Table 2):

Function 1: To power the hydraulic motor to move a vehicle
Function 2: To attach to the combustion engine

According to Eq. 1, we will have (5.5-1) / (10-1) = 0.50 which demonstrates an average degree of collaboration of components in the realization of functions.

Functional Dematerialization Indicator

According to Table 3 which precise the function EIA score, we can compute the functional dematerialization indicator.

From Eq. 2 we have:

$$DemMax = \frac{1}{2} = 0.5$$

This result shows a certain average level of intelligence.

The Functional Complexity Indicator

Before computing the functional complexity indicator, the list of factors with their score should be defined (Table 4).

From Eq. 3 we have:

$$ComplexiMax = \frac{1}{28} \times \frac{1}{2} = 0.02$$

This low number corresponds exactly to the product with very little coupling and therefore a low degree of mechatronics in terms of functional complexity.

Table 1: Incidence matrix of functions and modules

Two modules/two functions	F1	F2	Average
Module 1 (rotating assembly)	1.0	1	
Module 2 (fixed assembly)	0.0	1	
Number of functional modules contributing to a function	1.0	2	1.50
The average number of functional modules contributing to a function	0.5	1	0.75

Table 2: List of components with their function scores

Components/Functions	F1	F2	
Motor shaft and bearing	1,0	1,0	
Oscillating plate	0,0	1,0	
Retaining plate	0,0	1,0	
Piston	1,0	1,0	
Cylinder	1,0	0,0	
Timing window	1,0	1,0	IntegMax
Position sensor	0,0	1,0	0,50
Solenoid valve and hydraulic cylinder	1,0	0,0	
Number of components contributing to a function	5,0	6,0	5,50
Average number of components contributing to a function	0,5	0,6	0,55

Table 3: EIA function definition

Components/Functions	F1	F2	Total
Function EIA	1	0	1

Table 4: List of factors with their score

Mechanics	1	1
Electronic	1	0
Automatic	0	0
Computer science	0	0
Optics	0	0
Hydraulics	0	0
Thermal	0	0
Magnetism	0	0
Number of domains contributing to a function	2	1
Number of couplings contributing to a function	1	0

Table 5: Comparison of the main models in the literature

Authors	Tabourot and Balland (2017)	Leonida (2017)
Models	$IntegMax = \frac{\frac{\sum_{fonctions} NCF}{NF} - 1}{NC - 1}$ $ComplexiMax = \frac{1}{28} \times \frac{\sum_i NcoFi}{NF}$ $DemMax = \frac{NFEIA}{NFP}$	$IntegMax = \frac{\frac{\sum_{fonctions} NMF}{NF} - 1}{NM - 1}$ $ComplexiMax = \frac{1}{28} \times \frac{\sum_i NcoFi}{NF}$ $DemMaxEIA = \frac{NFEIA}{NFP}$ $DemMaxinfo = \frac{NFIf}{NFEIA}$ $DemMaxdiag = \frac{NFd}{NF_{EIA}}$ $DemMaxintev = \frac{NFIt}{NF_{EIA}}$ $DemMax = \sum_{i=1}^{i=4} \lambda_i \, DemMax_i$

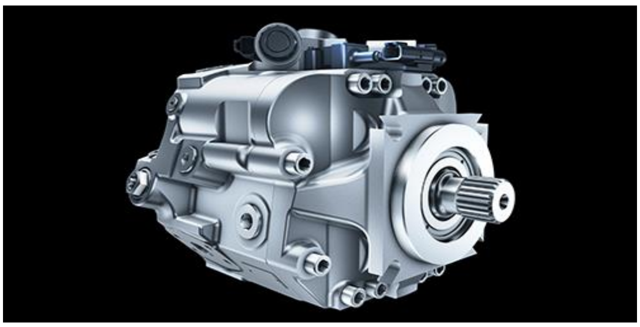

Fig. 1. Hydraulic pumps (Tabourot and Balland, 2017)

DOI: 10.3844/jmrsp.2022.57.64

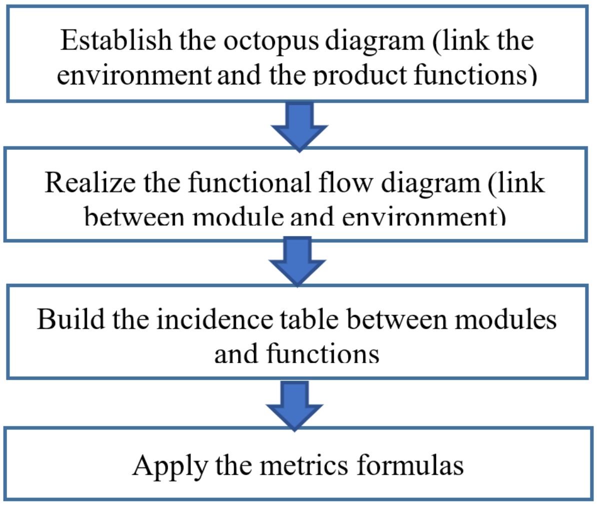

Fig. 2: Metrics application process

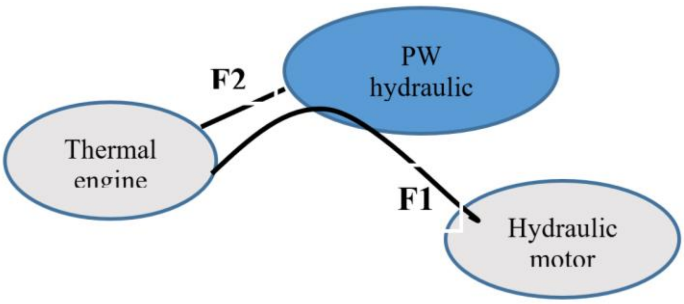

Fig. 3: Linking the environment and the functions of the Poclain PW product

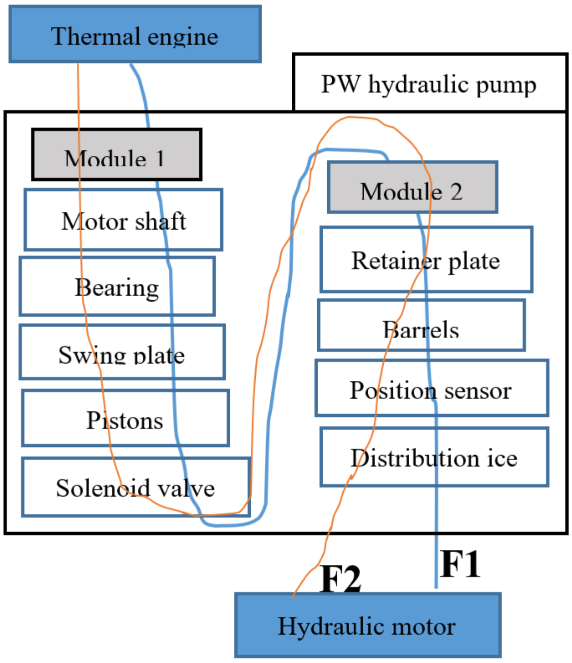

Fig. 4: Functional flow diagram of the pump components grouped into modules

Synthesis

For the metrics proposed by Tabourot and Balland (2017), the proposed IntegMax is interested in the components of the product and DemMax does not consider some functions generated by the presence of electronics, automation, and informatics; whereas for the metrics proposed by Leonida (2017), the proposed IntegMax is interested in the functional modules of the product and DemMax considers some functions generated by the presence of electronics, automation and informatics as illustrated in Table 5.

Conclusion

The models proposed by the authors, therefore, refer to the phase where the product functions have already been established as service functions of a product and extracted from the product catalog. Since the mechatronic functional product offering starts to be formulated from the early design phases. With the help of these metric models, it is possible to compare products of several generations of the same company, or between several manufacturers of the same products, and also between different products of different manufacturers by measuring the mechatronizability of different products.

Acknowledgment

This research is through with the sensible help of kind collaborators. I would like to thank some main referenced authors like Leonida and Tabourot who have provided the basic models for product mechatronizability that depicted the application methods of measuring equipment mechatronic degree. My institution has provided better accommodations in mechanics, material, and photonic laboratory which has facilitated research for Ph.D. students. Further collaborations in other to ameliorate mechatronizability for complex systems in the research field of holistic design will be always welcome.

Author’s Contributions

Jean Bosco Samon: Is the main author of this study because He defined the research topic. He designed the research plan, organized the study, contributed to the writing of the manuscript, and finally participated in all proofreading and reviewed the paper.

Brice Landry Tekam Guessom: Is the co-author of this article because he started research as a Ph.D. student on the measurement of the product complexity degree in the area of mechatronic application. He contributed to the writing of the manuscript and gathered essential data.

Ethics

I hereby the corresponding author of the manuscript declare that the manuscript titled: Analysis of Mechatronics Degree Evaluation Models, has not been published, that it is not under consideration for publication elsewhere, and that its publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out. It is not stolen or unsheathed from master's theses or doctoral dissertations that are not supervised by the author or of any other research. I take all the legal responsibilities in case this provided information is not correct. I make a sincere effort to ensure the accuracy of the material described herein. No fund has been received for this study. The use of part of the document or all of its content deserves to site the author or to seek his approval. I confirm that I have reviewed and complied with the relevant Instructions to Authors, Ethics in Publishing policy, Declarations of Interest disclosure, and information for authors. I am also aware of the publisher's policies concerning retractions and withdrawal.

References

Ajah, S., Al-Sherbaz, A., Turner, S. J., & Picton, P. (2015). Machine–to–machine communications energy efficiencies: The implications of different M2M communications specifications. *International Journal of Wireless and Mobile Computing* (IJWMC), 8(1). doi.org/10.1504/IJWMC.2015.0667

Bonjour, E. (2008). *Contributions à l'instrumentation du métier d'architecte système: De l'architecture modulaire du produit à l'organisation du système de conception (Doctoral dissertation*, Université de Franche-Comté). doi.org/tel.archives-ouvertes.fr/tel-00348034/

Bonjour, E., & Micaelli, J. P. (2009). Design core competence diagnosis: A case from the automotive industry. *IEEE Transactions on Engineering Management*, 57(2), 323-337. doi.org/10.1109/TEM.2009.2036838

Bonjour, E., Deniaud, S., & Micaëlli, J. P. (2013). A method for jointly drawing up the functional and design architectures of complex systems during the preliminary system-definition phase. *Journal of Engineering Design*, 24(4), 305-319. doi.org/10.1080/09544828.2012.737457

Bonjour, E., Deniaud, S., Dulmet, M., & Harmel, G. (2009). A fuzzy method for propagating functional architecture constraints to physical architecture. doi.org/10.1115/1.3116253

Bricogne-Cuignières, M. (2015). *Méthode agile pour la conception collaborative multidisciplinaire de systèmes intégrés: Application à la mécatronique* (Doctoral dissertation, Université de Technologie de Compiègne).doi.org/tel.archives-ouvertes.fr/tel-01213987/

Damjanović, V., Behrendt, W., Plössnig, M., & Holzapfel, M. (2007, June). Developing ontologies for collaborative engineering in mechatronics. *In European Semantic Web Conference* (pp. 190-204). Springer, Berlin, Heidelberg. doi.org/10.1007/978-3-540-72667-8_15

Demri, A. (2009). *Contribution à l'évaluation de la fiabilité d'un système mécatronique par modélisation fonctionnelle et dysfonctionnelle* (Doctoral dissertation, Université d'Angers). doi.org/tel.archives-ouvertes.fr/tel-00467277/

Djami, A. B. N., Nzié, W., & Yamigno, S. D. (2020). Disassembly evaluation in the design of a system using a multi-parameters index. *Modern Mechanical Engineering, 10(01), 1.* http://creativecommons.org/licenses/by/4.0/

Ericsson, A., & Erixon, G. (1999). *Controlling design variants: Modular product platforms. Society of Manufacturing Engineers.*

Fradi, M., Mhenni, F., Gaha, R., Mlika, A., & Choley, J. Y. (2021). Conflict management for mechatronic systems design. *In 2021 IEEE International Symposium on Systems Engineering* (ISSE) (pp. 1-8). IEEE. doi.org/10.1109/ISSE51541.2021.9582478

Leonida, Granon (2017). *"De la PME/PMI manufacturière traditionnelle à l'entreprise mécatronique: Étapes clefs et proposition d'un référentiel mécatronique*. Thèse de doctorat en Doctorat Sciences Pour l'Ingénieur à l'Université Grenoble Alpes (ComUE). http://www.theses.fr/2017GREAA021

Lo, M. (2013). *Contribution à l'évaluation d'architectures en Ingénierie Système: Application en conception de systèmes mécatroniques* (Doctoral dissertation, Université Montpellier II-Sciences et Techniques du Languedoc). https://tel.archives-ouvertes.fr/tel-00918890/

Pop, I. G., & Maties, V. (2010). Sustainable strategies in mechatronical education as vocational training environment. *Problems of Education in the 21st Century, 19, 94.*

Tabourot, L., & Balland, P. (2017, April). Evaluation du degré de mécatronicité d'un produit. *In 15e Colloque National AIP-Priméca.*

Turki, S. (2008). *Ingénierie système guidée par les modèles: Application du standard IEEE 15288, de l'architecture MDA et du langage SysML à la conception des systèmes mécatroniques* (Doctoral dissertation, Université du Sud Toulon Var). http://tel.archives-ouvertes.fr/tel-00344722/en/

Warniez, A. (2015). "Thesis: Integration metrics for the choice of architectures in the design of mechatronic systems." École Centrale Paris. https://tel.archives-ouvertes.fr/tel-01223145