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Metrics Generation Process for Mechatronics

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Due to the complexity of designing mechatronic systems, providers of these systems need to precisely evaluate their products, design processes and projects all along the design phase and beyond. We propose a metrics generation process and then define related specifications to develop an evaluation tool to build customized metrics for the mechatronic industry with respect to its specific process and expectations. The proposed process has been experimented on the modularity measure of two generations of vacuum cleaner robots.

Keywords: metrics; design process assessment; mechatronic systems; industrial monitoring.

1. INDUSTRIAL ISSUE & MECHATRONIC CHALLENGE

Today the industrial design process usually depends on each company's organization and on the design methods of their designers. It is more and more difficult for industry to respect reduced time-to-market without ending up over budget while designing ever more complex systems. Specifically, during the design stages, the objectives of the designers can be varied according to economic considerations, company strategy or market target and so on. So it becomes complex to identify the way to facilitate trade-offs for the different design choices [1].

For that, metrics are an interesting aid-decision support to help to formalize and trace the criteria on which the final decisions will be made. They provide support for planning [2], predicting, monitoring, controlling, and evaluating the quality of products and processes [3]. In the software engineering community, metrics have existed for long, since the sixties, and a lot of metrics and even assessment tools have already been developed to evaluate the complexity, the quality and the efficiency of software codes [4][5][6]. Jones, for example, has proposed four categories of metrics: quality measures, productivity measures, schedule measures and corporate measures [7].

Metrics can then be used for many objectives all along the design cycle. For example, they are useful for design process monitoring, such as requirements change

tracking, validation and effectiveness of reviews [8][2]. During the early stages of design, engineers and managers need also to evaluate projects and design concepts [9] and to predict their success [10]. Indeed, to facilitate design management, a first key precept would be to provide means of assessing different project attributes such as project maturity, schedule adherence, degree of innovation, amount of effective collaboration and level of effort (investment cost, new competencies), etc. Quickly after the project has started, design choices will arise, and metrics then can be helpful as a decision support for the system to be developed, to assess for example design choices, architecture and physical solutions choices, cost/earnings values [11], etc. Finally, a last interest of metrics for industry concerns the product quality evaluation: measure of performances [12], of effectiveness, of suitability, complexity, modularity, reliability, etc.

Although metrics have already been largely developed for software for decades [13], mechatronics challenges now address the same problematics but with multidisciplinary constraints, and few studies have proposed specific metrics for these complex systems [14][15]. For instance, in contrast to other industries, there are no standards or frameworks to assess mechatronic design processes. Today, too many mechatronic design processes are unique, depending on the experience or intuition of senior engineers, without any methodological support or validation. Since an important issue of mechatronic system design is that numerous design data are common to many involved engineering disciplines, it is crucial for designers and architects of such systems to provide predictive information earlier in the design cycle. Furthermore, the design of mechatronic systems generates such a wide solution space of possible designs from multidisciplinary specifications, that designers need efficient means to select the optimal solution within this space which will satisfy the large collection of mechatronics constraints. Finally, the increasing complexity of these systems due to their property to include connected and interactive multi-domain component parts makes it difficult to use the previous existing metrics specifically established for one domain. Indeed, mechatronic system design has to be carried out by different technical teams (Electronics, Automatics, Mechanics, Computer specialists), thus it is important to help them to choose

the optimal system architecture, to evaluate the project collaborative needs and also the global system reliability, by providing them with a means to build their own customized metrics, adapted to their structure, their product and their process.

The idea is to propose a process to build useful metrics for the mechatronic industry, so that any project managers' decision based on these metrics is traced and clearly justified. The presented method allows to build customized metrics in order to instantaneously evaluate the process, the project, the system design or the product quality, relating to identified mechatronic objectives.

2. CONCEPT OVERVIEW

The disadvantage of established existing metrics proposed by others is that these metrics usually fail to meet industrial objectives, as they usually do not "measure the right things in the right way, in order to take the right actions at the right time" [1]. To remedy this discrepancy and facilitate a better assessment of a project, a process, a system (to be designed) or a product (manufactured), it is important to first properly define the stakeholder's needs. The synoptic of the proposed customized "metrics factory" process is illustrated on Fig. 1.

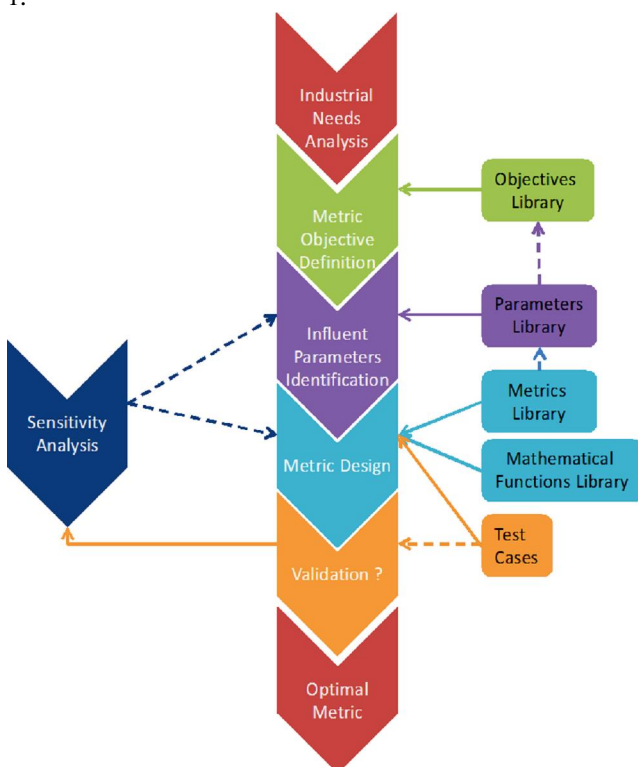


Fig. 1 Metrics Generation Process Overview.

Once the stakeholder's needs have been analyzed, one or more objectives to be evaluated have to be defined. For example, J.R. Smith explains that for the IT industry, the strategic objectives are usually global recognition, technology leadership, innovation and community satisfaction [1]. For mechatronics, it will be rather integration, robustness, maintainability, reliability, etc. A library of objectives could also propose some common

mechatronics objectives or others based on an internal database built on the company's own experiences.

After having defined the metric objective, metric designers can identify the obviously influential parameters of the chosen objective thanks to their know-how and feedbacks, or from a parameters library.

Then it is possible to design the metric which meets the previous objective, using the previous influential parameters, the identified reference test cases, whose expected value has already been estimated by metric designers, and possibly metrics or mathematical functions libraries.

If the mathematical formulation of the previous step is too difficult to establish or if the result of the metric tested on other industrial scenarios is not correct, a sensitivity analysis is recommended. This analysis allows then to correct both influential parameters and mathematical formulation of the metric, in order to build an improved one, until the optimal metric is achieved.

3. PROCESS DESCRIPTION

Prior to describing each step of the approach, we first need to define some common specifications to correctly build metrics. Then a sample objective of a mechatronic metric will be chosen to illustrate the process.

3.1 Prerequisites

In order to establish a scientific foundation and an evaluation of the built metrics, they have to fulfill some requirements, selected from Heinrich et al.[16], who describe more specific Data Quality metrics:

- Normalization: an adequate normalization is necessary to ensure that the values of the metrics are comparable to each other, and endure over time. In this context, metrics are often ratios with a value ranging between 0 and 1, limit values then represent the ideal value of the objective to reach and the one to avoid.
- Interval scale: in order to take into account the changes of measures over time and of economic variables, yet keeping normalization between 0 and 1, an interval scale must be properly chosen so that the difference between the assessments of two distinct elements shall remain meaningful. The same interval step shall mean the same change gap, whatever the initial value.
- Interpretability: expresses the ease for final users to interpret the value of the metric, so that each metric is comprehensible and the meaning of the value of each metric is universal.
- Feasibility: in order to make metrics usable, their input parameters have to be determinable, and their measurement methods should be defined. Ideally, costs must be considered, as a high level of automation in measurement methods will lower costs.

3.2 Mechatronics needs and objective definition

Needs Analysis

As mechatronic systems are multi-function, multi-domain, multi-physical integrated systems, they present during their lifecycle, a complex multi-faceted view that is difficult to analyze. The need for this industry to acquire a means of evaluation that is specific to its complex systems becomes crucial.

Stakeholders, who define the metric objectives, are key to this process, as they have to ensure that the new customized metrics meet the expectations of their mechatronics community. Their needs can be varied and will depend on the moment the metric will be used. As a rule, before the system becomes a physical product, these stakeholders are usually company members such as project managers, designers, etc., and then when the mechatronic product is manufactured, stakeholders become customers, marketers or sales people.

Stakeholders define a specific objective or can choose one predefined metric objective from an Objectives library. This objective could be relative to some indicators already predefined in their own industrial process. This objective can then be evaluated through different kinds of metrics that are classified into four categories: product metrics, process metrics, project metrics [17], and system (to be designed) metrics.

Product metrics assess features of the product, such as reliability, performance [18][19], etc.

Process metrics evaluate the quality, the collaborative aspect, the complexity of a process; for example, design, installation, maintenance, disposal processes. These metrics are usually based on time considerations, but also on loop and feedback patterns [8].

Project metrics describe the characteristics of a project and its execution, by evaluating, for example, the number of participants and their skill levels, schedule considerations, related costs, organization structure [20].

Finally system metrics are related to the evaluation of the system to be designed before it becomes a product with a physical body. They can support the design decisions regarding the choice of architectures, and assess for example the safety, the modularity, etc. of a system, depending on stakeholders' objectives.

Objectives Definition

A list of common objectives identified for mechatronics is given in Fig. 2 in accordance with this classification.

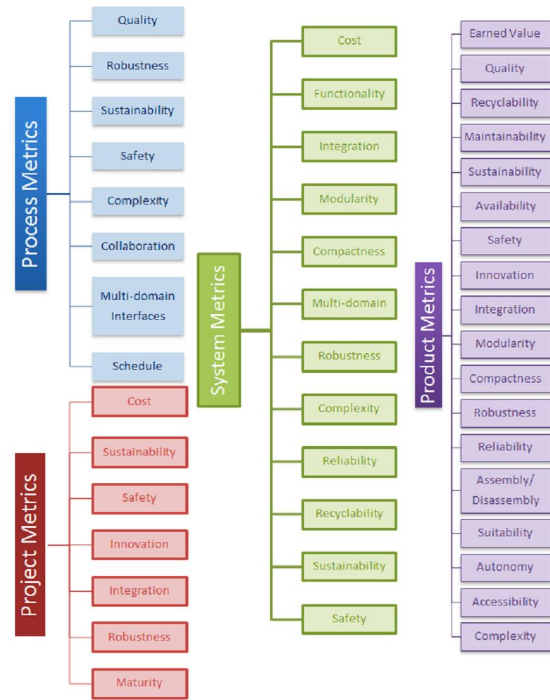


Fig. 2 Some typical objectives for mechatronics

The most important objectives for mechatronics are detailed hereunder.

The collaboration or the multi-domain interfaces in the design process of mechatronic systems are particularly important [21][22][23][24], due to the integration of multi-domain components, the involvement of different technical teams and corresponding interface management issues (such as the need of a common language for a unique view of requirements), the frequent collaborative reviews, the management of shared parameters and finally the trade-offs regarding the optimal solutions choices. Corresponding metrics evaluate how the design process efficiently manages these heterogeneous entities.

The assessment of the innovation level of a mechatronic project is critical due to the quick evolution of our society expectations. Indeed, those are based on new ITs and spectacular technological developments of more integrated and connected objects in reference to the "Internet of things" and Cyber Physical Systems [25], while time-to-market becomes increasingly shorter [26].

As mechatronics can be considered as an integrative discipline utilizing the technologies of mechanical engineering, electrical engineering/electronics and information technology and as they provide enhanced products, processes and systems, integration is a key point for design choices of mechatronic systems, be it functional integration, multi-domain integration or physical integration [14][27][28].

Even if the "Modularity" objective is obviously contrary to the above mentioned objective, it is particularly challenging for mechatronics systems, as it is difficult to access modules for change and maintenance when the system is designed in a small and integrated form. Indeed, modular design has currently become a

widely accepted developmental strategy to create products and systems that can be easily manufactured, upgraded and maintained by different teams, manufacturing methods, etc., using pre-defined modules as a basis of product and variant development [29]. Relating to the product, Ulrich et al. [30], even indicated that perhaps the most important characteristic of a product's architecture is its modularity. Modularity is particularly crucial for mechatronic systems: as they encompass various multi-domain components, their modularity influences their ease of service (disassembly and reassembly), the effort required to recycle them, and finally their cost.

Lastly, compactness is becoming a driving force in today's mechatronic systems, as increasing the number of components to be integrated in a compact volume generates desired or undesired multi-physical couplings. Actually, geometrical metrics to evaluate system compactness related to the components positioning are thus very useful to mechatronics designers [31].

Influent parameters

Industry usually manages many various data, but not necessarily useful ones. Therefore, its first challenge is to identify, from its own experience, the apparent influential parameters of the metric to be built. A good practice is to interview everyone who can influence it. Metrics designers can then either define the parameters that obviously influence the metric they are looking for, or they can choose them in a *Parameters library*. Furthermore literature reviews report some generic properties, from which influential parameters can be identified, such as:

- Cost: earnings, value [32], financial performance [1], etc.
- Time: process duration, task duration (design stage, simulation, manufacturing, assembling), etc. [33]
- Quality: of product (performances), of process (standards), of services (QoS) [34], customer satisfaction (perceived quality).

In parallel, the feasibility of the corresponding data collection has not to be neglected (see section 3.1). Extracting parameters by hand can be time-consuming, laborious and probably much error-prone.

Moreover, if the metric objective comes from the *Objectives Library*, it can be associated to some predefined relevant parameters which could also be proposed to the metric designers. These parameters can either have some discrete values or any predefined range of values. To verify if the chosen parameters are really influential in the metric to be designed, a sensitivity analysis can be processed. This "process" will be detailed in the next paragraph.

3.3 Metric Design

A metric is a mathematical combination of one or more directly measurable and accountable parameters. It can be built from basic mathematical functions like sum, subtraction, multiplication, division, but also polynomial,

logarithm, exponential functions or more complex equations. It has to be normalized to allow comparisons of the results and ranged, for example, from 0 to 1 (see section 3.1).

To meet industrial expectations, some predefined metrics (*Metrics Library*) can be proposed, based on literature reviews or on companies' feedbacks, and some basic mathematical functions (*Mathematical Functions Library*) with some rules (metrics have to be normalized, limited/ranged), in order to help the metric designers to build a suitable metric, gathering previously chosen influential parameters.

To facilitate this step, a sensitivity analysis is required to study how the metric varies when certain parameters change and a robustness analysis has to be performed with real industrial test cases, in order to test whether a satisfactory metric remains under different scenarios and several sets of data. It can be performed, by using a graphical display of the built metric in function of each influential parameter, in order to check that the corresponding evolution of the metric in function of this parameter fits with what the metric designer expects. Taguchi's Design of Experiment formalisms can also be a good approach to finely identify the suitable parameters and have a first good approximate of the mathematical formulation of the metric. The metric designers obtain then an improved metric with a better mathematical function and/or new identified influential parameters.

Next, the metric is built by computing instantiated parameters values from at least two reference test cases, whose expected metric values are provided by the metric designers. In some cases, they can only estimate their relative position with the "value distance" between both. Consequently they are then able to preview the "trend curve" of the mathematical function to choose.

3.4 Metric Validation

This validation step is crucial, because, if a significant discrepancy appears between what the built metric assesses and what managers or designers expected or experienced, the metric factory process would fail. Thus, built metrics have to be validated on real projects with real products and by real development staff. What existing metrics found in literature usually miss is their experimental validation. However metric designers have to compare the results of the built metric on several other test cases, to see how valid this metric is in their industrial environment.

If the relative scores to each test case do not satisfy industry expectations, then a new parameter sensitivity analysis could be performed to refine or improve the choice of the influential parameters and of the mathematical form of the metric, until the optimal customized metric is defined.

In fact, this validation step can take time and be achieved in two phases. When building the metric for the first time, the validation is conducted on two or three common test-cases, respecting the designers' "feeling" about the values of each test-case. In reality, to provide a

usable metric for managers to take their decisions, the metric has to be tested for several years, on various systems, processes, products, and has possibly to be adjusted according to their feedbacks, in order to be definitively validated.

Finally, anticipating the related data collection issues before assessing the designed metric on real test cases is highly recommended. Indeed, collecting data has to provide useful information for process, project and product assessment, without being a burden on development teams. Even if at the beginning of the metric building process we need to collect a lot of parameters values on the reference test-cases, to precisely identify the pertinent information and thus the influent parameters, it is important, as much as possible, to define which data will be needed for the considered metric to avoid a wasteful over-collection of data. The predictability of the influent parameters and the adequate mathematical form of the metric is all the more self-evident, that enough empirical data have been accumulated. In some cases, these data need also to be validated before being used [17], especially when no automatic data collection with validation routines has been implemented.

4. CASE STUDY

For the case study, we have chosen to illustrate the modularity objective to evaluate vacuum cleaner robots architectures.

After presenting the mechatronic case study, composed of two test cases of vacuum cleaner robots, a brief state-of-the art of industrial challenges related to product modularity will be described, before experimenting and validating the metrics factory process.

4.1 Industrial test cases description

Mechatronics is increasingly involved in the successful development of domestic robots, be it for humanoid robots (e.g. Nao robot) or for specific home appliances (like lawnmower robots, automatic shirt ironing machines). Currently, the most developed ones are floor-cleaning robots; millions of these devices are indeed used to vacuum people's homes nowadays. [46].

The Roomba is a robotic floor vacuum cleaner capable of moving about the home and sweeping up dirt as it goes along. It is a logical merging of vacuum technology and intelligent technology. These machines move themselves autonomously across the floor, brushing or vacuuming dirt and dust into a dustbin. It undertakes three types of cleaning, using two rotating brushes that sweep the floor, a vacuum that sucks dust and particles off the floor, and side sweeping brushes to clean baseboards and walls. Infrared signals are used to determine the Roomba's current location in a room, and to ensure that it does not fall down the stairs or off raised floors. A set of sensors is also used to determine dirty places on the carpet that need more attention. The Roomba returns to a self-charging home base after the floor is cleaned up or when it needs to recharge [47].

Moreover, with the evolution of technologies, domestic robots shifted from the simple random-walk approach towards more evolved navigation schemes, involving a localization technology at an affordable price.

Finally, the main requirement of Roomba robots is to have several capabilities so that they fulfill the following tasks: a navigation strategy within the environment, a cleaning device, and some kinds of interactions with the user, at least to start and stop the cleaning process. An energy storage and management unit powers these functions.

In this case-study, two generations (the third and the fourth) of Roomba have been used as testcases: the Roomba 565 and 765, whose main evolutions concern the following aspects: a new Aerovac dust bin (serie 2 with increasing capacity) with a double HEPA (High Efficiency Particulate Air) filter, a more robust cleaning system (improved dust handling) with an advanced cleaning head, a better dirt detection (smarter algorithm), an improved battery lifespan, and finally a dust bin fullness indicator.

4.2 Industrial challenges for modularity

Modularity based on the decomposition of a system into subsystems and components, facilitates standardization and increases the variety of products [35]. As companies increasingly focus on streamlining their product lines by providing a growing diversity of products at the lowest cost, modular design has become a development strategy widely accepted in many industries. As these modules can be then manufactured in relatively large volumes, the logistics of production is eased while reducing manufacturing lead time. As a result, modular products and systems can then be also easily redesigned and maintained by different teams, different methods etc., working on predefined modules as product development basis and its variants [38].

Actually, the modularity-based design of a product has a strong influence on its whole lifecycle [36][37]. Modularity allows then designers to manage unexpected design process changes more efficiently, by giving designers further flexibility. This flexibility enables for example to postpone design decisions until more information is available without delaying the product development process. When focusing on architecture modularity, Ulrich et al. state that it is the most important characteristic of product architecture [18]. Accordingly, Hehenberger underlines the pros and cons of an integrated or a modular architecture in Fig. 3 [23].

| Integral Design | Modular Design |
|--|---|
| + Function and structure integration | + Function- and/or manufacturing-oriented product structure |
| + Low number of parts | + Utilization of purchased parts |
| + Low number of internal couplings | + Flexibility, interchangeable modules |
| + Miniaturization | + Easy to maintain and repair |
| - Complex geometry | + Modular design system |
| - Special materials | - High number of parts |
| - Interdependence of sub-functions | - High number of internal couplings |
| - Maintenance and repairing difficult (disposable product) | - Assembling and setting costs |
| | - High required space |

Fig. 3 Pros and cons of integrated and modular design [23].

4.3 Application of the developed process to the case study.

As we have no industrial partner that could experiment the proposed metrics generation process in real conditions, we have illustrated the case study by using public information (for Roomba description) and modularity metrics extracted from literature, in order to simulate the proposed process.

- Industrial needs analysis

Considering robots, architecture modularity is particularly interesting [39], since modular design makes part replacement trivial and thus improves the system maintainability [40]. Moreover, as the revolutionary developments in information and communication technologies have resulted in a rapid evolution of robots, easing their upgrading, by adding new functionalities without redesigning all their modules has become crucial [41].

- Metric objective definition

A module can be defined as a physical element of a technical system, which has a clear and explicitly defined interface and is totally self-contained, while providing known and particular functionalities. Architecture modularity metrics have been widely used in different contexts, ranging from the design to the manufacturing of electrical, mechanical products and software. Hölttä-Otto et al. [17] present two main types of modularity metrics ó those that assess module independence by measuring the degree of coupling and those that identify similarities between modules.

The former metrics consider the architectural linkage issues between elements with strong and loose couplings permitting degrees of isolation. It should be pointed out that the couplings between the different modules are of critical importance especially for mechatronic systems, because the interactions are not restricted only to one discipline, but extend to beneficial links between different disciplines. Hence, all the disciplines of the mechatronic systems have to be concurrently treated, ideally from the beginning of the design process [42] and especially when considering the modularity objective.

The latter metrics consider the ability to use the same materials, manufacturing processes, suppliers, and the ease of reuse or recycling, etc. These properties are assumed to be achieved if functions or components with similar properties are grouped together in a module. For mechatronics, it represents the capability of mechatronic modules to be used in more than one solution or in building other mechatronic systems.

- Influential parameters identification

According to the architecture or design phase addressed, be it functional, logical or physical, different parameters can be considered. For example, functional and logical architectures could make appear some data and connecting elements that would allow to predict the quantity of connections between functions, and thus contribute to define the modularity of the design.

Concerning physical architecture, the number of physical connectors between mechatronic subsystems, whatever the related physical flow types (information, energy, material, spatial) [45], could also be a good indicator to evaluate the modularity of the final product.

Therefore, according to S. Turki [44], when addressing a mechatronic module (physical or conceptual grouping of components of one domain) [43], the number of input and output flows of each module can also be considered as influential parameters.

- Metric design

To illustrate the metrics factory process, we propose a first modularity metric extracted from literature. The considered metric given by P. Hehenberger [23] addresses the similarities between the functional and the physical architectures of a product in order to define the modularity of a module based on its functionalities. This metric, named Mechatronic Modularity Index (*MMI*) aims at evaluating the reusability of a module in another system (with a same sub-function) or at re-designing a module with minimized effects on the rest of the product. Considering a functional structure tree to describe the relationships between the different functions (F) and sub-functions needed to achieve the requirements of a mechatronic product, the physical architecture provides a number of mechatronic modules N_m that will realize these functions. The modularity index is established by a relation between the number of all the system functions N_F and the number of all mechatronic modules N_m . The *MMI* is then described by:

$$MMI = \frac{N_F}{N_m} \times 1$$

The expression values range from 0 to 1: the higher the *MMI* value is, the more modular the solution is. Actually, this metric does not properly fulfill the four metric prerequisites: the normalization condition is only fulfilled when $N_F > N_m \times 1$. The interval scale is not representative, since *MMI* does not make a difference between two architectures having only one module with a different number of functions, since *MMI* is null in all cases. Concerning its interpretability, *MMI* is remotely interpretable, since a value near 1 means a high modularity, but *MMI* can be hard to interpret, since it does not indicate whether the considered modularity is concentrated in one or several modules. Finally, the feasibility is respected, since it is really easy, in practice, to count the number of considered functions and of modules, provided that the functional architecture has previously been unanimously validated.

A critical constraint is that the N_m has to be lower or equal to N_F , otherwise it would mean that the functional decomposition has not been sufficiently deepened. In fact, this metric directly depends on the (detail) decomposition level used by each designer to provide both the functional and physical architectures. Therefore this metric does not permit to reliably compare two generations of products that have not been designed by the same person or with the same architecture design level.

- Validation

Therefore, we have supposed that the metric designers were not satisfied with this metric on their test case (vacuum cleaner robot) and thus that they want to proceed to an iteration to find a better metric, by adding new influent parameters (number of physical flows) and building a new mathematical expression, as previously described.

We assume that the resulting metric is the one proposed by S. Turki [44], which consists in measuring the intra- and inter-module connectivity. This metric, named Module Autonomy Metric (*MAM*), is defined when designing a logical architecture, by the ratio between the number of strictly internal connectors (i.e. interfaces of one physical flow) of a module and the total number of connectors (also comprising the external ports of the system towards its environment). This means that it focuses on the relationship between internal physical flows and those with the external environment, since module autonomy improves the modularity and reuse of systems.

Considering:

NCSI: number of strictly internal connectors

NCB: total number of connectors in the considered system.

$$MAM = \frac{NCSI}{NCB}$$

This metric is normalized and bounded between 0 and 1. The closer to 1 the result is, the more independent the module. In Fig.4, the *MAM* is of 0,71.

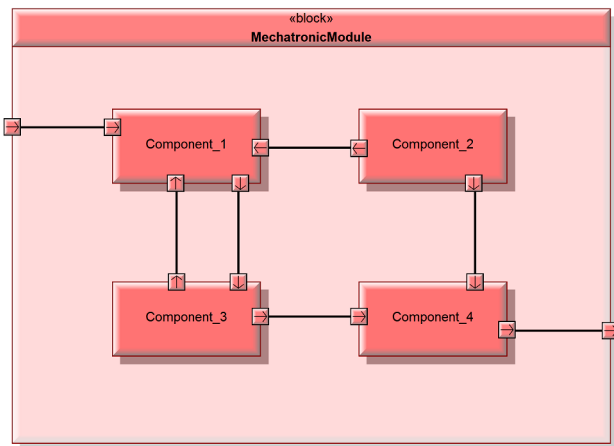


Fig. 4 Example of a mechatronic module logical architecture.

Considering metric prerequisites of *MAM*, the normalization rule is respected, since the total number of connectors is necessarily higher than the number of internal ones. Moreover *MAM* is equal to 1 when there is no external connector, which corresponds to the maximal modularity level of a module. The interval scale is not correctly performed, since the same gap between *NCSI* and *NCB* will not have the same impact on the *MAM* value and this may not be representative of the metric designers' wish. Concerning its interpretability, *MAM* is remotely interpretable, since even if a value near 1 means a high modularity, it does not indicate whether the considered modularity is concentrated in one or several modules. Finally, the feasibility is respected, since it is really easy, in practice, to count the number of connectors, provided that the logical architecture has previously been unanimously validated.

Finally, as metrics designers can foresee the expected modularity value of both test cases, they use the latest generation of vacuum robot (Roomba 765) architecture to validate or not the latter proposed metric they have designed on the former generation of Roomba (565 Pet), to be sure that the designed metric suits their robotic products.

4.4 Results

Both metrics have been experimented on both Roomba generations, based on SysML modeling. Functions allocation to each module has been presented on a Block Definition Diagram, which allows to allocate the corresponding functions to each module. The Fig.5 illustrates the model of Roomba 565. The example on a logical architecture of the mobile system of the Roomba 765 has been given in the Fig.6, to show the different interactive flows existing between the modules.

The results of metrics calculation are represented in the Table 1.

These results underline the importance of the metric choice made by designers, since it can a direct influence on defining the most 'modular' product. Regarding the metrics generation process, if the i-Robot company considers, from its own feedback, that the new Roomba 765 is more modular, metric designers will choose a modular metric taking into account the physical flows between components, like the *MAM* metric, rather than the functions-components allocation rate of the *MMI* metric.

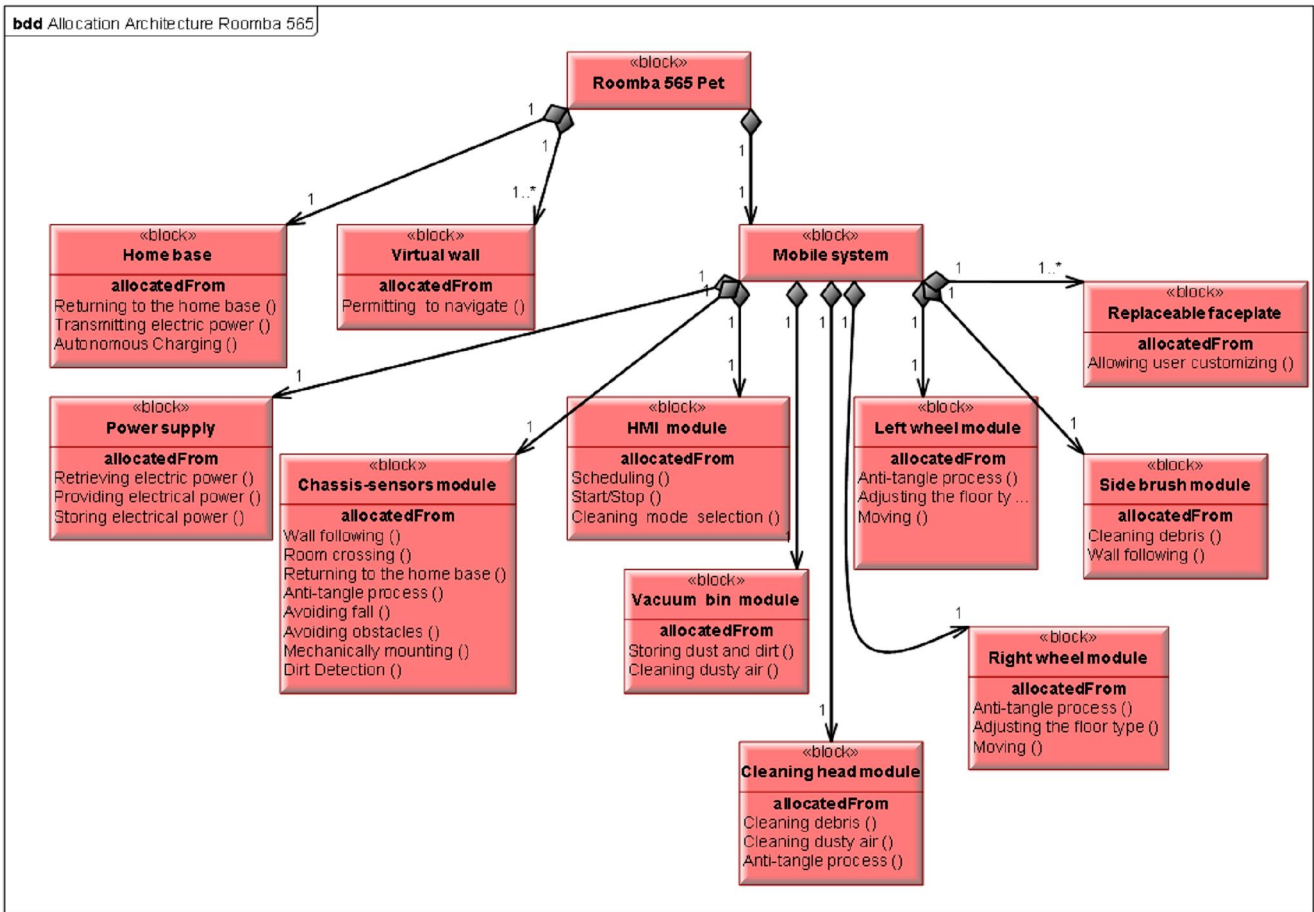


Fig. 5 Function allocation architecture of Roomba 565 Pet.

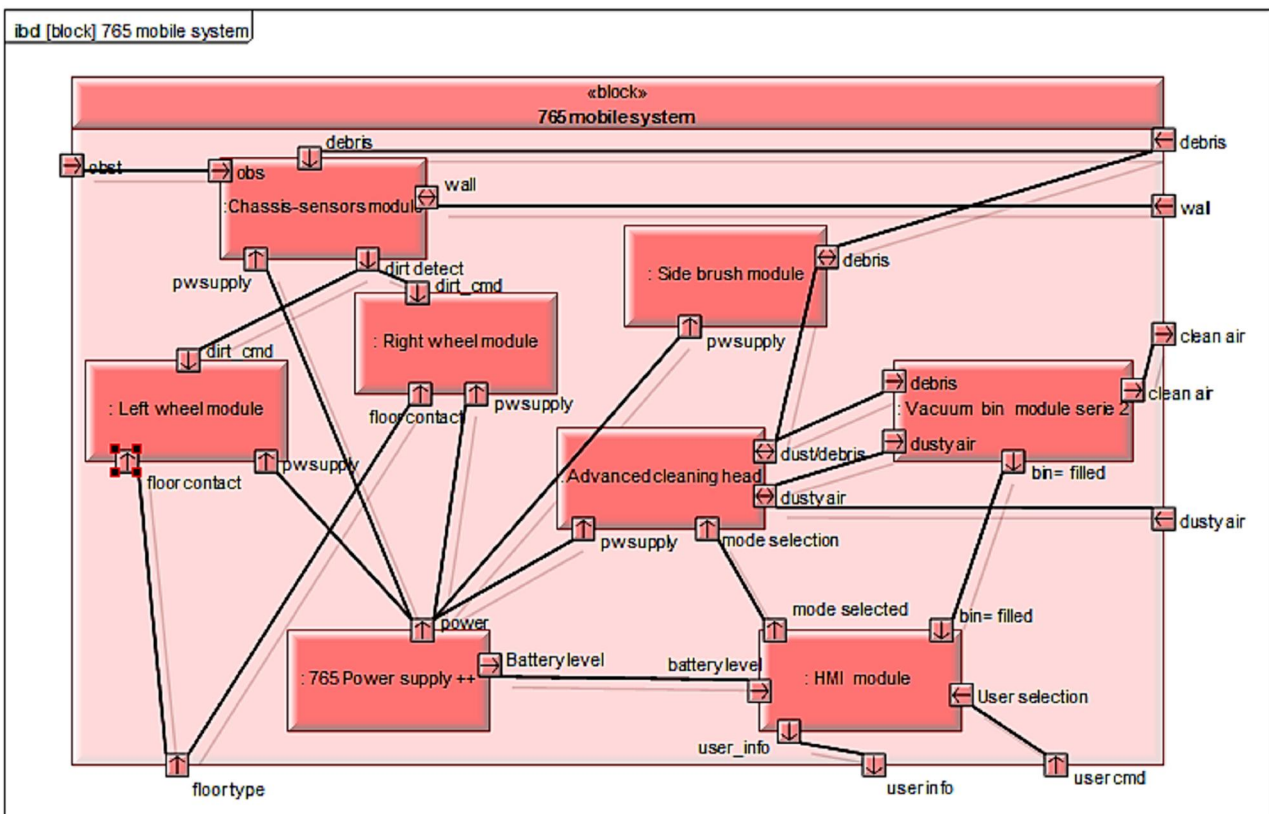


Fig. 6 Logical architecture of 765 Roomba mobile system.

Table 1 Comparison of metrics results on both test cases.

| Metrics | Roomba 565 | Roomba 765 |
|------------|------------|------------|
| <i>MMI</i> | 0,32 | 0, 26 |
| <i>MAM</i> | 0,44 | 0, 47 |

5. DISCUSSIONS AND FUTURE WORK

A metric has to be specific for an industry and an objective, but if there are different objectives to take into consideration to facilitate trade-offs between different points of view (disciplines, designers, services), the metric building process is the same for each metric, and a lot of multi-objective optimization techniques [48][49][50], or techniques based on weighting considerations can be used to achieve an optimal global metric.

The validity of this process has yet to be proved in a real industry, by automatizing the metrics factory process, through a δ metric frameworkö linked to existing industry data bases or PLM systems.

Concerning the deterministic value of the metric, how can we guarantee the pertinence and the realistic assessment of the built metric? Our approach is based on the use of normalized metrics and real use cases for validation (cf. 3.1). If a metric has to be used for a long time (over decades or different generations of products), the influent parameters, or reference values can evolve and it becomes essential to redesign the metric, relying on a calibration update including a validation process on new test cases. This exercise is particularly difficult, when considering innovation metrics or process metrics, because a significant change (of society, technologyí) can call into question the metric pertinence. A given product, even in the same product range, can be so different that it does not allow to be assessed with the same parameters. Typically, if we observe the difference between the first circuit breakers (whose function was mainly to automatically protect an electrical circuit from damage caused by overload or short circuit) and the current smart connected ones (that are fully integrated to smarter houses, allowing to control energy consumption, energy regulation, etc.), it is obvious that the objective of the product modularity or of product integration cannot be considered in the same way. With the advances of the mechatronics discipline, customersø expectations and technical challenges have evolved so quickly -and it will be worse with the IT revolution towards new Cyber Physical Systems- that the metric parameters based on current designersø competencies, methods, tools cannot remain the same, as they will not be sufficient to take into consideration the economic, environmental, social and technological evolutions. Thus, we should maybe have to consider that a metric has a life duration, which determines the time period during which we suppose that it will remain valid.

After defining the optimal metrics, we can also imagine to use artificial intelligence (AI) tools and techniques to select the best design concept, architecture, product, etc. with the highest or lowest metric values, from a solution space generated by system designers.

Finally, a basic feature of a metric is to be measurable. Therefore, it is important to succeed in formalizing every parameter in mathematical expression, even δ humanö parameters (human competencies, individual behavior, personal working methodí). To achieve this, a lot of research studies focus on δ humanö modelling, either on biomimetic approach, or on cerebral behavior, to improve the experience-based systems smartness. Finally, why not imagine δ smart metricsö using AI techniques to be automatically enriched with new parameters, when the sensitivity matrix changes or human factors become no longer negligible in the results obtained.

6. CONCLUSIONS

As new IT evolution is so quick, shortening time-to-market, mechatronics needs, to remain competitive, a means to build appropriate metrics, to provide predictive information earlier in the life-cycle reducing late design changes and their corresponding exorbitant costs. Unlike in more mature scientific fields, it appears difficult in mechatronics engineering to imagine a δ universalö set of metrics that can be suitable for all applications environments. The proposed process to build customized metrics, usable in the early stages of mechatronic design process, will allow a better management of the later phases, and a more effective quality assessment, when product quality can still be easily improved by preventive or corrective actions.

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SUPPORTING ONLINE MATERIALS

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