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COMPLEXITY AS INFORMATION CONTENT AND ITS IMPLICATIONS FOR SYSTEMS DESIGN

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1. Introduction

Although system thinking and systems methodologies can be traced back up to the ancient Greeks, complexity is still a remarkably ambiguous and vague term that assumes different insights according to different disciplines. Complexity is a recurrent word in biological systems [Koch and Laurent 1999], [Weng 1999], [Csete 2007], [Mazzocchi 2008], computer science [Branke et al. 2006], [Mitchell 2009], philosophy [Morin 1992], [Kim 2006], economics [Arthur 1999], [Farmer 2012], management [McCarty 2006], [Tilebein 2006], and engineering, just to mention a few. The number of works on this topic and the width of the discussion surely highlight its importance, but they also emphasize that we are still far from a general and comprehensive definition.
As far as engineering design is concerned, such lack is not a problem, as long as it is clear the definition in use every time. It undermines anyway, a more general and coherent discussion on how complexity affects the design activity, what are the methods and tools currently used to tackle it, and how much the best practices are effective. These questions become even more important as several sources [Bar-Yam 2002], [Lindemann et al. 2009] claim that "complexity" in society, market and technical products is increasing. Furthermore, in the last decade, engineering is taking inspiration from the field of Complex systems science to develop new methods and tools for the design of "complex systems" [Frei and Seregundo 2011a,b], [Zapf and Weise 2007], whose novel paradigm and terminology can further increase the ambiguity of the word.
The present work aims at building a definition of the word "complexity" that is consistent with previous literature and is able to clarify some aspects of the practice in the engineering design of systems. An extensive literature review of the authors, still to be published, has highlighted the different meanings that "complexity" has in different fields; however, this is not the scope of the present work. The objective is rather to focus on key aspects that must be taken into consideration when developing theoretical work regarding systems design, both in the analysis of current practices and in the synthesis of new methods and tools. The definition proposed is not meant to be imposed as the final truth on the topic, but rather it would foster a useful debate to clarify different perspectives on systems design and to pursue a better understanding of it. The ultimate goal is to use such definition as a reference to classify models, methods and tools in the field through a homogeneous framework.
The main body of the paper is organized in three sections. First of all, five key features of complexity will be underscored from multi-disciplinary literature on complexity. Then, a new definition will be proposed, in order to synthesize the five different aspects in a coherent and complete perspective. This definition will prove its usefulness in the analysis of the Systems Engineering design practice, with particular focus on requirements definition and functional decomposition. Finally, the conclusion section will summarise the results and will provide future research directions.

2. Five key concepts about complexity

Lloyd [2001] lists more than 40 measures of complexity, but many others have been proposed in literature. A research in the Scopus or ISI Web of Knowledge databases does not offer many means for clarification: as shown in Table 1, complexity is employed very commonly, in various fields and with different meanings and measures.

Table 1. Results of different queries related to complexity in scientific article databases (data retrieved on November 25th, 2013)

Topic/Keyword(s)	Database	
	ISI Web of Knowledge	Scopus
Complexity	More than 400,000	152,221
Complexity AND definition	7815	389
Complexity AND design	68,288	11,470

Instead of summarizing such a huge literature, this section focuses on five key aspects of "complexity" for engineering design and recognizes their appearance in a set of previously existing definitions. The definitions are taken from different areas; some of them are related to engineering design, others to complexity science or philosophy. Even though their origins are disparate, they all refer to a system property usually called "complexity", which has a fundamental impact on the methods and tools for systems design. Under the assumption that some properties of systems are invariant regardless of the specific domain of application, it is possible to take advantage of knowledge from different domains in order to define what complexity is, how it influences engineering design and why it is so relevant. The five key aspects proposed in this paper (Figure 1) are: size of the system (in terms of parts or subsystems), observer's effort, relation with modelling language, information content, and sub-classification of different aspects related to complexity.

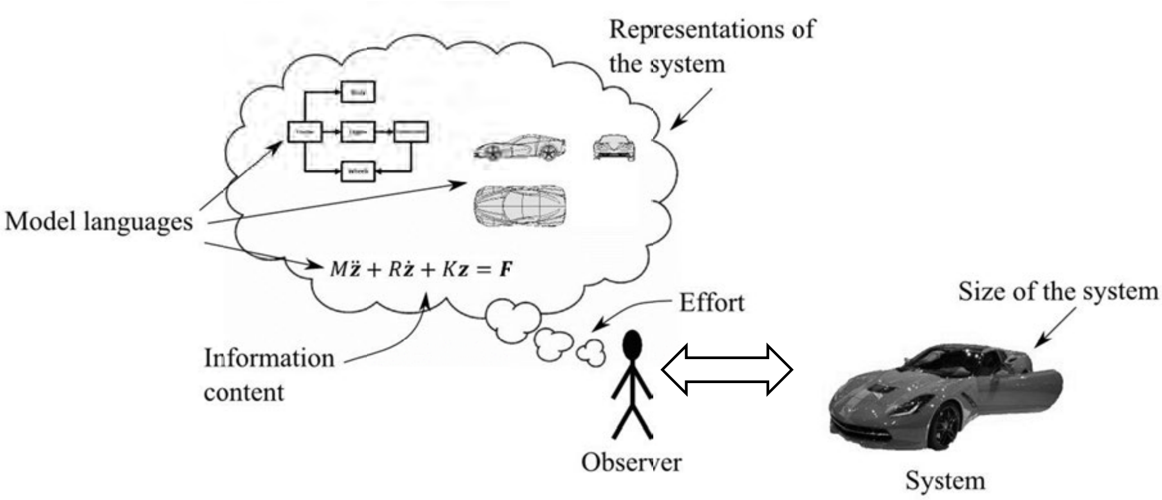

Figure 1. Graphical representation of the five concepts of complexity

It is evident that complexity has a quantitative aspect in its roots. For example, in the field of complex systems engineering, [Bar-Yam 1997] identifies the complexity of a system as the number of possible states in a system, and [Norman et al. 2006] indicates the volume of a "characterization hyper-space". From the field of engineering design, [Weber 2005] counts directly some entities in the design process, like number of components or number of variants, while [Magee and Weck 2004] and [Simon 1996] state that a system is complex only if it is composed by "numerous components" or by a "large number of parts".

Another relevant trait in the definition of complexity is the relationship with the external observer of the system. Several works relate complexity to a perceived "difficulty" in understanding the global properties or behaviours of a system from the properties and behaviours of the parts. This is evident in

[Edmonds 1999] 's definition of complexity, but also in [Magee and Weck 2004] and in [Simon 1996]. It is relevant to mention that the duality between the system and the *perception* of the system is a key aspect also in the definition of Emergence [Deguet et al. 2006], [Kim 2006], which is very close to the concept of "complexity" according to Complexity Science and Complex systems engineering [Frei and Seregundo 2012], [Ronald and Sipper 2001]. What is Emergence, how it can be defined in engineered systems and when does it arise during the product development process are extremely interesting topics, but will be discussed in a next publication.

Both size and observer's perception lead to the idea that complexity cannot be separated from a modelling language. The concept is central in the thesis of Edmonds [1999], when he claims that complexity is linked to a language or framework, but it is also assumed in [Bar-Yam 1997], where "states" imply a state-space description of the system, and in [Suh 1999], where functional requirements (FR), Design parameters (DP) and their relationships are all elements of a modelling language.

If complexity is related to the adopted language, then it can be quantified by the information content of the description. Algorithmic complexity [Kolmogorov 1965], one of the most famous definition of complexity in Computer Science, associates complexity with the minimum amount of information necessary, defined as "the size of the smallest program of an optimal universal Turin machine generating that string". Complexity can be also related to the length of a schema [Gell-Mann 1995] or to the information required to achieve the FRs of a design in Axiomatic design [Suh 1999].

Finally, complexity can be further classified according to several criteria or dimensions of characterization. [Weber 2005] proposes the use of five dimensions to evaluate the complexity in the design field. Interestingly, the author does not consider only features linked to the technical system, but also organization type. Another classification is provided by [Suh 1999], who distinguishes six different kinds of complexity, according to time dependence and designer's knowledge.

These five aspects and all have a significant importance in the characterization of complexity in engineering design; all the definitions above capture some important features of complexity, but without a comprehensive and systematic characterization.

The following section tries to combine these aspects in a new, exhaustive definition consistent with the previous ones. The overall goal is to provide a mean for a more precise and consistent discussion about the design of systems in the future.

3. Defining complexity

After examining five key concepts about complexity largely discussed in various fields, a new definition of complexity is proposed. To do that, first it is important to distinguish between the aim of design, what is commonly called "system", and its abstract representation, the "holon". Complexity is associated to the information content of a "holon". Given that the systems design is concerned with the interaction with system, complicatedness is introduced as the observer's effort in processing the information due to complexity. Finally, this section proposes a characterization of different aspects related to complexity also through an illustrative example of a railway vehicle suspension.

Systems and holons

"System" in engineering design can boast a wide characterization. A system (in engineering design) has been defined as "a combination of interacting elements organized to achieve one more stated purposes" [Haskins 2006]; technical artefacts can be treated as technical systems [Hubka and Eder 1988], which can be divided into subsystems and has input/output relationships with the environment (what is outside the system's boundary).

Engineering design usually assumes that systems are ontological aspects of reality: the world outside the designer is made up by different systems related in different ways. This paradigm is usually called "Hard systems thinking" and dates back to General Systems Theory [Bertalanffy 1968] and Cybernetics [Wiener 1948].

To deal with systems in social sciences, Checkland and other authors changed this paradigm in a new theory, Soft Systems Thinking [Checkland 2000]. According to their movement, a system is an epistemological concept ascribable to an observer. In order to avoid misunderstandings, Checkland

proposed the use of the word “holon” instead of system; “holon” must be used “whenever we refer to the abstract concept of a whole or build a model of a holon (models being always descriptions of holons which might or might not map onto some bit of real-world complexity)” [Checkland 1988]. In social sciences, the use of holon allows agents to realize that the perception of system can or cannot be shared by other agents; therefore, it is important to consider each single stakeholder’s perspectives about individual holons before taking common action.
The concept of holon can be very useful also in engineering design, since it shows how systems design is carried out through partial representations of the system itself. “Systems” can now refer to the objective of design, the technical artefacts resulting from the design process. Every system can have one or more technical holons, defined as the abstract concept of a technical system. Technical holons can be mathematical models, functional models, structural architectures, technical drawings, CAD models… Holons can be used both to study the behaviour of systems (analysis), to synthesize the final design of systems (synthesis) and to choose between different alternatives (choice). Every technical holon describes the (technical) system partially, and different holons may be combined to achieve a better overall representation. There are at least four evident aspects regarding the technical holon:

1. Every technical holon is a representation of both the technical system and its relevant interactions with the environment;
2. Every technical holon is created to achieve a certain objective;
3. Every technical holon has a specific language;
4. Every technical holon has specific assumptions, both declared and latent. Generally, these assumptions are determined by knowledge and/or resources available.

The four features are relevant in understanding why a technical holon is chosen and why it is different from other technical holons of the same systems.
As an example, the secondary suspension subsystem of a railway vehicle is considered. The suspension is composed by a series of mechanical organs that connects the bogie to the carbody of a vehicle. Many technical holons can describe this system, depending on the objective of the description:

- Suspension can be represented in a functional modelling language. Several languages can be used, like EMS (Energy-Material-Signal) functional modelling, SysML (Systems Modelling language), IDEF0 (Icam DEFinition for Function Modelling, where “ICAM” is an acronym for Integrated Computer Aided Manufacturing) or FRs and DPs relationships.
- A suspension can be seen as a dynamical system with inertia, stiffness and damping. In this case, the language of description is mathematics and several assumptions can be made according to the goal of the technical holon. If the aim is to provide a rough analysis, a linear model of a three degree-of-freedom vehicle can be sufficient, while if the complete behaviour at low frequencies is the matter of interest, a dynamical non-linear model with rigid bodies is more appropriate. On the other hand, if the range of frequencies of interest extends to the ones involved with passengers’ comfort, not only the springs but all parts must modelled as a deformable body with its own stiffness and damping.
- A suspension can be described as a mechanism to be produced. In this case, the relevant aspects are the quality and the cost of production; the environment of the technical holon, i.e. the representation of the manufacturing system, can impose some constraints and requirements, for example on the shape of the components;
- A suspension can be depicted as a bill of materials, i.e. the parts it is composed of;
- A suspension can be drawn in a technical representation to communicate the shape and the dimensions of the assembly among several engineers.

Complexity

The introduction of the technical holon is the first step to define complexity. Being an abstract representation, a holon is defined by its language and consists of interconnected information. It is assumed that complexity is related to the holon, not to a system. Complexity is here defined as the information content of the holon itself. The definition is coherent with the five key points illustrated in the previous section. The information content is related to the “size” of the system described; technical holons are representations of the system and are depends on the representation language used. Furthermore, as stated in literature, each system has different aspects that contribute to the definition of complexity: this is reflected in the use of different holons in the description of a system. Some further insights concerning the role of the observer in the definition of complexity will be proposed in the following sub-section.

This definition, therefore, agrees with the five key aspects underscored in section 2, but it also allows further reflections.

The information content assessment can be performed in accordance with the specific language of the holon and it is related to the “size” of the system itself. There are several measures of complexity in literature [Edmonds 1999], [Lloyd 2001] that can be used in this regard, but new measures can also be designed according to the specific holon of interest, provided that they are consistent with the definition. The reason why there are so many proposed definitions regarding complexity can be explained by the presence of many different holons in the scientific and technical world.

Complexity depends on the characteristics of the technical holon: its objective, its language and its assumptions. Many engineers might feel uncomfortable with this definition, because it seems subjective in nature. The same system can have different complexities according to the technical holon provided, therefore complexity depends on how single engineers model the system. This aspect should not be perceived as a drawback, since defining complexity as a property of representations and models can lead to a clearer discussion about which aspect of a system is “complex” and why. This is considered one of the main improvements that the proposed definition of complexity can bring.

In order to clarify the definition of complexity proposed above, two different types of secondary suspensions for railway vehicles are evaluated. The first suspension is a traditional anti-roll bar made up by passive mechanical parts: it usually consists of a torsion spring linked to the bogey and to two connecting rods, which in turn are hinged to the vehicle’s carbody. When the carbody rolls with respect to the bogey, the two connecting rods provide a torque to the torsion spring, which opposes the relative motion. The other suspension is equipped with a hydraulic anti-roll bar (Figure 2) that provides active vibration control [Colombo et al. 2013]. In this case, two linear hydraulic actuators installed at the left and right sides of the bogie are actively controlled. This innovative suspension not only resists the roll (as the traditional anti-roll bar), but is also able to generate a relative motion between the carbody and the bogey during curve negotiation in order to increase the passenger’s comfort.

Intuitively, the active suspension appears more complex than the passive one, but, without a proper analysis of different holons, “complexity” remains a vague notion. Four technical holons are therefore proposed for each of the two systems, taking inspiration from the list provided in section 2.

For the functional analysis, an EMS functional model is chosen (Figure 3). Both suspension change the mechanical energy transmitted from the basement to the frame and vice-versa, but the hydraulic anti-roll bar is able to provide a second function. In fact, it can also transforms the energy from the electric generator and the displacement signal from the carbody in order generate a relative roll angle between the carbody and the bogey.

The linear, half vehicle dynamical model of the two suspensions shows significant differences between the active and the passive one. Considering the overall vehicle suspension, a suitable index can be the number of poles of the linear dynamical model (Figure 2). In case of a PID controller, the index increases from 6 (traditional anti-roll bar) to 10 (active anti-roll bar), since 3 poles are added by the controller and one by the dynamics of the actuator.

Since the hydraulic anti-roll bar is still a concept, information regarding the manufacturing process and the structural architecture can only be estimated roughly. A possible index for manufacturing complexity could be the number of working processes required to produce the system. In this case, it is clear that just the assembly phase of the active suspension requires much more tasks than the one of the traditional suspension. The same can be supposed regarding the number of hardware components, which are taken as a suitable index for structural complexity. While the traditional anti-roll bar is composed of an assembly of mechanical parts, the active anti-roll bar proposed requires a pump, reservoirs, pipes, hydraulic cylinders and computer hardware. It is evident therefore that the structure of the active suspension is far more complex than the structure of the traditional one.

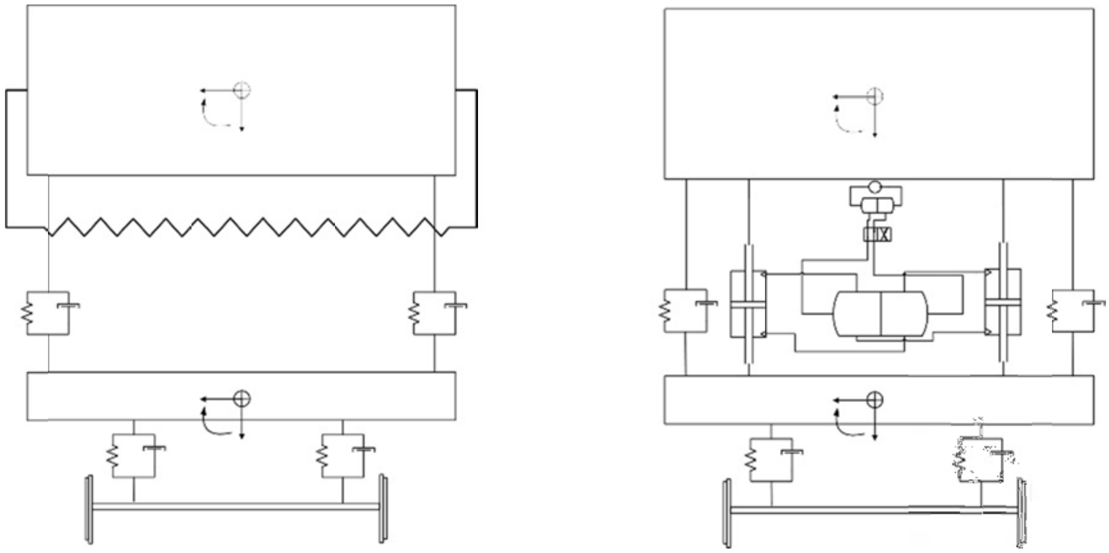

Figure 2. Linear dynamical model of railway vehicle equipped with traditional anti-roll bar (left) and active hydraulic anti-roll bar (right)

Complicatedness

It has been noted that a relevant component of complexity is given by the relation between the observer and the system. In the proposed definition of complexity this aspect has been deliberately avoided, since complexity has been associated with the information content of a representation, the technical holon. The notion of the observer's perspective anyway retrieved through complicatedness.

Complicatedness is described in [Ehrlenspiel 2009] as "the subjective difficulty in interaction with technical systems that often depends on one's personal abilities". [Sinha et al. 2013] similarly describe complicatedness "an observer-dependent property that characterizes an actor's / observer's ability to unravel, understand and manage the system under consideration". More generally, complicatedness is defined here as the effort required by an observer in order to process information about a technical holon.

Complicatedness is a function of complexity, but also it depends on the observer's (the designer's) own characteristics. As an example, [Sinha et al. 2013] cite novelty of an application and cognitive bandwidth of the designer or group of designers. More insights on how designers deal with complicatedness are given in section 3, which analyses the System Engineering design process.

Complicatedness can be evaluated only indirectly. There can be two main classes of measures: one refers to quantifiable characteristics of the design process, the other on mental workload.

Development cost and time are two examples from the first class. Development time has been proved to increase exponentially with complexity both in [Sinha et al. 2013] and in [Bashir and Thomson 1999]. In the first case, the time required to assemble a chemical structure is compared to a network-based definition of complexity; in the second case, the time required to develop a product is associated to the depth of a functional analysis.

Mental workload evaluation can be carried out either dynamically during an experience [Rouse et al. 1993] or statically at the end of the experience. If it is evaluated dynamically, measures of different body parameters like temperature and eye movement are required, while if it is gauged statically, many evaluation methods can be found in literature [Hart and Staveland 1988], [Reid and Nygren 1988].

4. System Engineering and complexity

System Engineering is described as "an iterative process of top-down synthesis, development, and operation of a real-world system that satisfies, in a near optimal manner, the full range of requirements for the system" [Eisner 2011]. Its origins can be traced back to huge defence and aerospace programs after the Second World War and it has become a reference for the development of technical systems with several industrial and academic conferences and many publications every year.

Systems engineering is here taken as reference to prove the usefulness of the definitions provided in the previous sections and to point out how design methods can address complexity and complicatedness.

Systems engineering envisages a comprehensive life cycle management description of processes and techniques that deal with technical systems. Since the scope of the paper is the characterization of complexity in systems design, the analysis will be limited to the Concept and Development stages [Haskins 2006, p. 3.7] and to the Technical processes [Haskins 2006, ch. 4].

Complexity in Systems Engineering

First of all, to evaluate complexity suitable technical holons of the system have to be chosen. Two different technical holons from Systems Engineering will be considered, the list of requirements and the functional decomposition. The choice is justified by their importance in the design process, their popularity and their ability to describe every kind of technical systems.

Requirements The list of requirements is one of the basic tools in Systems engineering, as also stated in the INCOSE definition [Haskins 2006, p. 1.5]. The list of requirements contains all the requirements derived from the needs of the stakeholders and from other systems at higher or lower hierarchical level. Two processes are dedicated to the definition of the requirements (Stakeholder requirements definition process and Requirements analysis process), but requirements also propagate through the entire functional decomposition, therefore are fundamental through the entire design process. According to Systems engineering, systems design starts with the definition of requirements and ends with the verification and validation of requirements.

The list of requirements as a technical holon can be represented in two ways: on the one hand, requirements are limitations imposed to the design solution space; on the other hand, they can be seen as connections that a system has with its environment through the life cycle. The degree of complexity (the information content provided by the list of requirements) is given either by the number of requirements, or by the number of stakeholders and systems involved. It can be assumed that complexity in requirements holon arises because the environment in which the system operates is various, dynamical and usually uncertain [Lindemann et al. 2009]. The description of how the complexity inside the system is influenced by the complexity of the environment is surely an interesting topic worth further research.

Functional decomposition Functional decomposition is a method to identify subsystems through the detailing of system's functions [Eisner 2011]. Functional decomposition can be performed according to different technical holons [Kapurch 2007]: product breakdown structure, functional flow block diagram, N-squared diagram, IDEF0 diagrams [Buede 2011], Design Structure Matrix [Browning 2001] and many others. These technical holons can be subdivided into two main categories according to language similarities: block-like holons and matrix-like holon. For the first class, complexity can be defined as the number of sub-levels in the hierarchical decomposition [Bashir and Thomson 1999] or the number of nodes and links; for the second class, a suitable measure would be the dimension of the matrix.

Complexity is generated by the number of functions provided and the interactions between system parts. As P. Corning noticed in [Corning 2003], technical systems are created because the function to be performed can be achieved only through the cooperative effects of several parts. The combined effect of these parts is called "synergy". There are two types of synergy, depending on the observer judgement: positive synergies are considered beneficial since they are related to desired functions, while negative synergies are undesired effects born from unexpected or undesired parts' couplings.

Complicatedness in Systems Engineering

Complexity poses a serious challenge to efficiency in design. As described in section 3, there is evidence that the effort required to design a system increases exponentially with respect to complexity. One of the key challenges to systems design is therefore to address holons with high complexity

without increasing excessively complicatedness. In this respect, two features of System Engineering are paradigmatic: the systematic method for design and the role of functional decomposition.
A systematic method for design abstracts the features of a specific technical system to a more general one that can be designed according to common practices. In this way, the novelty aspect is mitigated and designers can retrieve mental schemas already present in their mind. In Systems Engineering these schemas are exemplified in very abstract process models like the Vee model [Haskins 2006, p. 3.8] or the doctrine of successive refinement [Kapurch 2007].
Reducing complexity in technical holons in order to decrease the effort in the design and management of the system is a common paradigm [Lindemann et al. 2009, p. 2]. In this respect, the definition of technical holon can provide means for a more structured discussion. The main topic is the appropriate degree of complexity of a technical holon. Making simplification assumptions reduce the complexity of the holon thus decreasing complicatedness, but an excessive reduction of the information content can prevent the holon from giving a sufficiently detailed or correct representation of the system. A very common example in the design of dynamical systems is linearization. Assuming that the system changes around a point of equilibrium, non-linear relationship can be simplified thanks to mathematical procedures without compromising too much the prediction of the dynamical behaviour of the system (objective of the holon). If the objective of the technical holon is the description of the behaviour of the system far from the equilibrium point, the assumptions are no longer valid.
Functional decomposition tries to overcome this issue thanks to the independence of functional subsystems. If subsystems can be separated, their holons can be studied, designed and substituted independently from the others, since the coupling effects do not exist or are irrelevant. The complexity of a single subsystem is a fraction of the complexity of the entire holon, therefore also complicatedness is reduced. Unfortunately, technical systems are "nearly decomposable systems" [Simon 1996], therefore even if functional decomposition is very sound in theory, it presents some difficulties in practice. Several algorithms and techniques have been developed to achieve a satisfactory decomposition [Lindemann et al. 2009], but it seems that some properties like sustainability cannot be properly achieved through systems decomposition and requires a different design approach [Charnley et al. 2011], [Umeda et al. 2012].

5. Conclusion and research directions

The aim of this work is to highlight some important features of complexity of systems design in order to propose a sharable new definition. Five aspects of complexity have been chosen and described as a preliminary analysis. After introducing the notion of technical holon as an abstract representation of a technical system, two separate concepts were defined: complexity has been formalized as the information content of the technical holon, while complicatedness has been characterized as the effort to process the information content of the technical holon. Finally, System engineering was taken as a reference methodology to prove the suitability of the proposed definitions and to specify how complexity and complicatedness are addressed in an emblematic design methodology.
First of all, a general catalogue of the technical holons used in Engineering disciplines would be very interesting, in particular in the fields, like Mechatronics, where multiple different modelling tools are used to reflect the different disciplines involved in the design.
As far as complexity is concerned, suitable measures for different kinds of technical holon must be compared in order to point out the most meaningful ones. A list of complexity measures associated with the respective technical holons would be of great benefit to the design community, since different design could be compared according to standard measures and the effectiveness of different design practices could be better understood. Furthermore, it is often assumed that complexity in technical systems is increasing [Lindemann et al. 2009]. A historical analysis of technical holons could confirm this impression and discover what are the reasons for the growth of complexity in the technical world, similarly to what Complexity Science is researching in the biological world.
Complicatedness poses some challenges, too. First of all, since complicatedness is related to design effort, it would be interesting to explore the relationship between complexity, complicatedness and mental processes in design activity. While complicatedness and complexity are exponentially related at project level, the correlation between effort and single mental processes is still obscure. In

particular, it is envisioned that the situated FBS (Function – Behaviour - Structure) ontology [Gero and Kannengiesser 2004] can be a reference framework to perform this analysis. In particular, it should be possible to analyse how each process is influenced by the complexity of the system and relate a certain effort to each process. The outcome would be a more detailed description of the complicatedness and some guidelines for the development of methods and tools to design systems with limited effort. Secondly, the relationship between experience and complicatedness has not been demonstrated. Some experiments are needed to prove the assumption and to promote the use of educational method to increase the ability of designers in system thinking. Finally, the field of engineering design would surely need a description of how complexity in technical systems arise and why, similarly to what is discussed in the field of biology.

Another interesting topic worth of investigation is the development of methods and tools for the reduction of complicatedness without a decrease in complexity. At a first glance, some directions are already present in design literature: for example, the use of automation in design can relieve the designer of part of the effort. Another possible source of inspiration is the field of interface design [Vicente 2002], [Letsu-Dake and Ntuen 2010] or Infographics [Ciuccarelli et al. 2010]. Their combined knowledge can grant the correct amount of information so that designers do not reach a mental overload, or it can provide a suitable representation of the system to foster new ideas and the comprehension of technical holons.

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