A literature survey of multiple discipline integration keywords, based on a process, model, and knowledge classification

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***Abstract*— Integration is still one of the main issues that multidisciplinary design faces nowadays. However, due to the lack of a precise definition and variety of contexts that use the term integration, it is very challenging to find relevant literature reviews on the topic. To solve this issue, we used a process, knowledge, and model classification approach, which generated a large set of highly relevant and varied publications. Using this large amount of literature, the contribution of this paper consisted on identifying a set of relevant keywords (~130), grouped in 14 categories. These keywords and categories support the literature search in the topic of integrating the system design with the detail design according to the multiple discipline detail design. Furthermore, by assessing the type of outlets and level of testing, we concluded that the topic is still in its infancy, having a lot of activity in recent years and still establishing possible research directions.**

Keywords*— systems engineering, multidisciplinary integration, interdisciplinary integration, product design, systems integration, design knowledge, design process, model-based, literature review

I. Introduction

Due to the fast pace in which market changes and technology advances, constant innovation is a key factor for a company's success. Normally, most innovation happens at the boundaries between disciplines or specializations [1]. Working across boundaries is, in fact, one of the main reasons that innovation proves to be so difficult to create and maintain [2] and constitutes some of the key factors for product innovation success [3].

Choi & Pak [4] point the fact that life in itself is multiple disciplinary and the division into domains or disciplines is, in fact, an artificial fragmentation of knowledge. Currently, to achieve advancement we are driven to broaden our scope of investigation beyond the boundaries of the existing disciplines [5]. However, this requires modern mechanisms which do not exist in engineering disciplines today, to match the vast modern complexities required for engineering solutions [5]. According to Sage & Lynch [6] *technical integration* was identified as one of the top four issues faced by systems engineers from major U.S. Department of Defense (DoD) contractors. In fact, they noted that integration is generally always being performed, but it is not clear as to where it is performed or how to accomplish it successfully [6].

This lack of coordination, interfacing, and integration during the design process can lead to [7]:

- Product release delays
- Extra engineering
- Unforeseen changes
- Poor quality
- Budget and product cost over-runs
- High maintenance costs

Because of the huge impact it has on the design process and in general in the system and product lifecycle, systems integration is an activity omnipresent in almost all of systems engineering and management [6]. The integration of subsystems and components is what creates the real value of the system under design, generating behavior that would not occur if the elements do not work together integrally. We will consider multidisciplinary systems integration at the product level in our efforts to follow.

One of the biggest problems in the study of integration, as clearly noted by Sage & Lynch [6], is that the term lacks precise definition and is used in different ways and for different purposes in the engineering of systems. Due to this ambiguity, literature reviews or any kind of overviews on system integration approaches are hard to find or lacking.

Not surprisingly, the authors tried to find literature on the topic of multiple discipline integration, without much success. The first approach involved a quick scan in the Scopus database for the expression "system integration", which led to several thousand results at the point of writing this paper. The results were very diverse and with questionable relevance concerning the design process. In hopes of focusing the direction of the results, the keywords "systems engineering" were added to the search. This resulted in less than a thousand results at the point of writing; however, the relevance of the results was still in question due to the enormous variation of topics, application areas and meanings of the word integration. Virtually no literature review was found. This means that the literature is so

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scattered and the word *integration* is so ambiguous, even within systems engineering, that finding its state-of-the-art, and particularly identifying current approaches for multiple discipline integration, is a challenging task.

Therefore, the present paper provides a different perspective to support the search for literature on the integration topic. The objective was to determine a set of keywords to support the search of meaningful papers that tackle with the problem of integrating the system design with the detail design according to the multiple discipline detail design. Instead of using *integration* as a keyword, we propose to search the solutions offered by systems engineering based on an organizational point-of-view classification of *knowledge, processes, and models*. Because of the amplitude of the classification, the presented analysis includes a large amount of papers and is based on keyword search. As a result, we aim at presenting the reader with a mapping of the different paths being explored in the literature to solve multiple discipline integration issues. The upcoming sections will describe our motivation for the aforementioned classification framework, the research methodology, and finally our results along with a brief discussion of the limitations of the study, and our conclusions and future work.

II. APPROACHING INTEGRATION FROM AN ORGANIZATIONAL POINT-OF-VIEW: PROCESS, KNOWLEDGE, AND MODEL

An often-neglected matter is the fact that the design process occurs normally within an organizational (social) context. Verhagen, Stjepandic, & Wognum [8] note that todays' distributed product development teams need to manage both human (organization) and technical (product and process) elements of their work.

Because of this duality of social and technical aspects, lately research has focused on so-called *socio-technical systems*, which describe systems that involve a complex interaction between humans, machines and the environmental aspects of the work system [9]. For a review on socio-technical systems design, the reader can refer to [9].

While this paper does not pretend to assess in depth the human aspects of collaboration, we aim at taking an organizational change point-of-view as a base to create a different perspective on classifying multiple discipline integration approaches.

To do so, we part from the organizational change model proposed by Harold Leavitt in 1964. Leavitt's organizational change framework views the organization as a complex system consisting of four main variables: task variables, structural variables, technological variables, and human variables [10]. More recently, and loosely based on Leavitt, Smith & Koenig [11] presented a model-based design process by means of the development of *people, processes, and technology (models)* in aerospace culture. Furthermore, Moser & Wood [12] indicate that the elements of the system can be identified as the *people*, *processes*, and *means* and they are tightened together by organizational arrangements. More completely, Blessing & Chakrabarti [13] describe design as a complex, multifaceted phenomenon, involving: *people*, a developing product, a *process* involving a multitude of activities and procedures; a wide variety of *knowledge*, *tools* and *methods*; an *organization*, as well as a micro-economic and macro-economic context.

Estefan [14], based on Martin [15] proposes what he calls *PMTE* elements. These elements are *Process, Methods, Tools* and *Environment*, and he describes as well, the effects that technology and people have in them. To have a broad and powerful look at these aspects, we propose to adapt the triad of *people, process, and technology (PPT)* in combination with Estefan and Martin's *PMTE* elements to provide a framework for classification and analysis of the systems engineering approaches towards integration.

Based on the combination, the three distinct aspects will be defined as:

- **People = Knowledge:** for this aspect, and based on Estefan [14], we will focus on what we consider one of people's most valuable assets in the design process: their *experience and (domain) knowledge*. As complexity increases, an ever smaller fraction of the design knowledge is documented [16]. For a basic system component, 80% of it gets registered and, in contrast, only 30% is documented for a simple system [16]. The remaining 70% is tacit knowledge encapsulated in the experiences of the designers [17].
- **Process = Processes + Methods:** According to Martin [15], a *process* is a logical sequence of tasks performed to achieve a particular objective. A process defines "What" is to be done, not specifying "How". For the "how" exist *methods*, that consist of techniques for doing a task and at any level, tasks are performed using methods [15].
- **Technology = Tools = Models:** In this aspect, we would like to focus particularly on the point of view of the *tools*, i.e. as the enabler of the process and methods. A *tool* is an instrument that, when applied to a particular method, can enhance the efficiency of the task [15]. Estefan [14] defines *methodology* as the collection of related processes, methods, and tools. To be more concrete in the technology/tools aspect, we want to concentrate our search on the new paradigm of using *models* or *modeling languages* as common-ground tools for communication and integration in systems engineering.

Using the previous definitions, we argue that integration of multiple disciplines can be approached either by means of *establishing processes (process-based), managing people's knowledge (knowledge-based), using neutral common-ground models (model-based)* or a combination thereof. Fig. 1 shows the proposed classification.

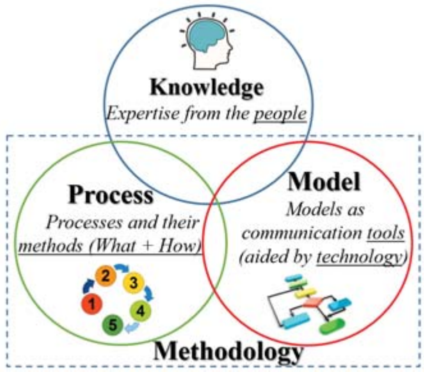

Fig. 1. Proposed classification framework with categories of knowledge, processes, and models

III. RESEARCH METHODOLOGY

As we discussed before, the literature for systems integration or multiple discipline integration is very dispersed and hard to find due to the ambiguity and different uses of the word integration. Because of this, and based on the classification shown in the previous section, we determined a systematic procedure to approach the literature search.

- *Database selection:* Due to the generality of the integration topic and the broadness of the words in the classification framework, we considered that a search in one peer-reviewed general database would be satisfactory to obtain a representative set of publications. The choice was between Scopus and Web of Science (WoS), as both remain today the main sources for peer-reviewed citation data. To make a choice we refer to Gavel & Iselid [18] who analyzed the journal coverage overlap between Scopus and WoS. Based on 2006 data, they showed that, at the time, 54% of active titles in Scopus were also in WoS and that 84% of active titles in WoS were indexed in Scopus. From this, we concluded that, for the general results that we sought, a search in Scopus would be sufficient.
- *Keyword selection:* For each category of approaches, we selected two relevant search expressions. To keep it general and yield a substantial quantity of results, the first expression of each category consisted of the original word and the word "design". The second were selected as expressions that could help obtain more quality results for each category. The selected keywords were:
    - **Process:** we selected the expressions "*design process*" and "*design method**". For the latter, words such as methodology will be obtained as well.
    - **Model:** The first expression was "*design model*". For the second we chose "*model-based systems engineering*", because it was specific enough to give high quality results, but broad enough to get different approaches.
    - **Knowledge:** the first expression was "*design knowledge*". The second one was word "*design variables*", because it is a way of connecting knowledge.
    - **Systems Engineering:** The aim of this was to have provide context to the expressions within systems design.
- *Final query:* **("design method*" OR "design process" OR "design model" OR "model-based systems engineering" OR "design knowledge" OR "design variables") AND "systems engineering"**, looking in title, abstract and keywords. Fig. 2 shows the final search query.
- *Citation/Relevance selection criteria:* To reduce the number of hits to analyze and still guarantee the relevance from the set, we applied a citation criterion.

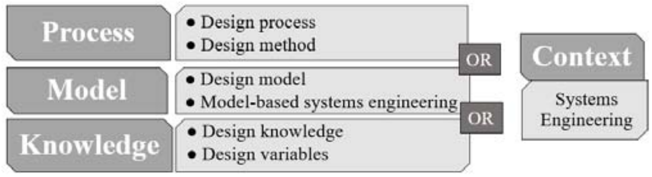

Fig. 2. Final search query

    - Papers older than five years (2013-older): Only papers with a minimum of five citations were selected to continue with further screening.
    - Papers of five years or less (2014-present): No minimum citations were considered, therefore all these papers were taken into the next round.
- *Theme selection criterion:* The resulting titles and abstracts were reviewed to determine if they were relevant to the design process. The criteria was set to topics related to *general design research or design process of physical products or software architecture*. The first term refers to notions on how to do design. For physical products we considered those having at least one physical component and for software the ones addressing architecture design.
- *Final cut:* From the filtered list, we proceeded to manually search for the full-text version of the papers. In doing so, many papers were left out of the list due to: (1) the paper was not in English; (2) it was not possible to access the full-text.

From the keyword search, at the time of writing, 3492 papers were found in Scopus. After applying the citation criteria, the list was narrowed down to around 2000 papers. After the second theme-related criterion was applied, 1280 papers remained, from which the full-text was manually searched. Based on language an accessibility of the results, the final cut contained 1023 papers. Due to this large amount of papers, the authors chose to carry out some of the analyses based on keyword searches. The software that was used to obtain a word list per document was *Atlas.ti 8©*. The lists were automatically generated and consist of *single* words only, thus no expressions were included.

IV. RESULTS

A. Maturity of the topic

The notion of the state of the research area is often referred to as its level of maturity - essentially, whether the research area is new and highly theoretical or has been more developed with some convergence on best practices [19]. Given this, we propose to look at two factors that can be related to the maturity of the topic: a) Type of outlets, b) Level of testing.

a) Type of outlets

According to Keathley-Herring et al. [19] one of the possible criteria to assess the maturity of a topic is the type of outlets. The corresponding metric that we have selected to analyze is the proportion of papers by outlet type. The graph from Fig. 3(a) shows that up until around 2013, the highest number of papers correspond to journal articles. This is not surprising as journal papers have normally more impact, and the older papers were selected based on their amount of citations. After this year, we note an incremental tendency for the conference papers, which culminates in them surpassing the amount of journal articles in 2011. This could indicate new approaches or theories emerging around this time. For the years between 2011 and 2014, the increment in the number of papers from both journals and conferences is notable, which means that a lot of activity took place around those years. This upward tendency seems to continue in the last 5 years, depicted in Fig. 3(b).

However, in these last years, the notable predominance of conference papers indicates that the new propositions/approaches have not yet reached maturity to become journal articles. This behavior denotes a research area with low maturity, where a lot of effort is still put into formalizing the approaches to the topic.

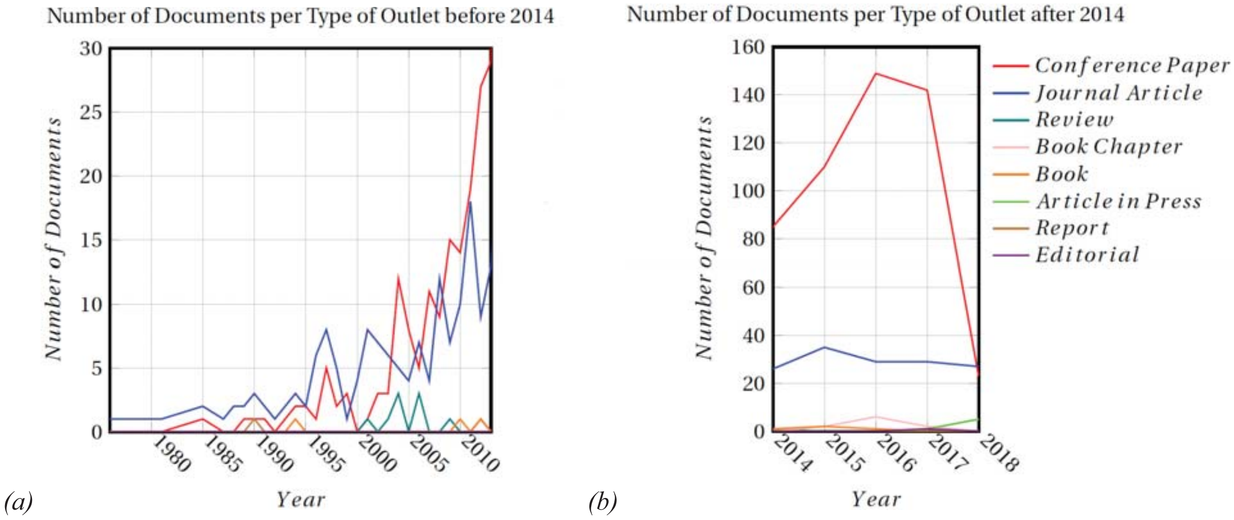

Fig. 3. Number of documents per type of outlet: (a) before 2014, (b) after 2014.

b) Level of testing

Again referencing the work of Keathley-Herring et al. [19], we took a second angle to assess the maturity of the topic by analyzing the level of testing of the approaches. The keywords for more conceptual testing were *case* and *example*, and for more active testing, *industry*. The graph in Fig. 4 shows us that cases and examples constitute the main basis for testing in the selected papers. Even for the papers older than 2014 (left side of the dotted line), which had a high impact based on their citations, the assessment of the proposals was still mainly conceptual. For these papers, it can be noted that industry is mentioned in average in less than 20% per year, while cases and examples are more frequently used (with around 40% and 30% of the papers, respectively). The right part of the graph contains the newer papers, which were only selected based on their relation to the topic. As we can see, for those tendency to mainly use cases and examples still prevails. Nonetheless, it is worth noting that in the last couple of years the testing of the research area has slowly increased to mention the industry. In general, these results correspond to more conceptual phases of research, where cases and examples are prominent and industrial applications are less frequent. This situation best fits with the analysis phase of research framing, indicating low maturity of the topic.

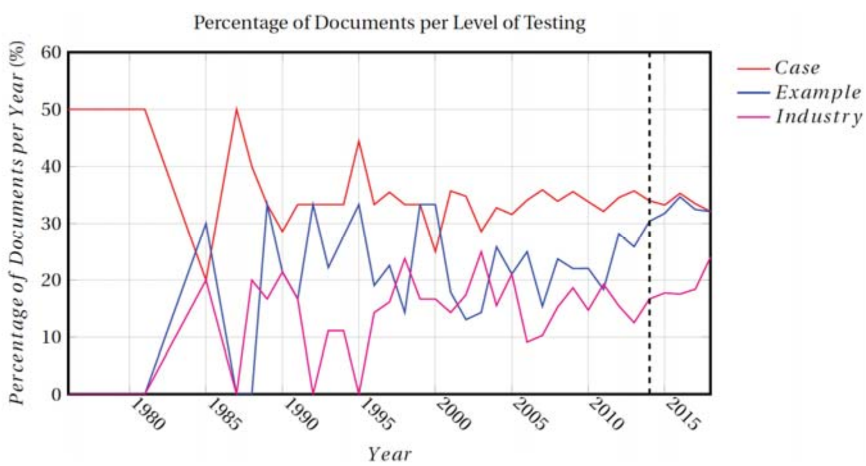

Fig. 4. Percentage of documents per level of testing

B. Relevant keywords found in the literature

The systematic research methodology of the present paper was meant to yield a diverse and representative amount of results, given the proposed classification of process, knowledge, and model related approaches. One of the main reasons behind analyzing this large amount of publications was to find the most relevant keywords that can indicate tendencies or paths that are currently being explored as solutions. To make it manageable for the Atlas.Ti© software, documents were divided into 4 batches of approx. 250 papers. The total number of distinct words/symbols found by the software was around 180,000. To find the most relevant keywords from each batch, only the words with at least 25 occurrences (10% of the batch size) were taken. This yielded a list of approx. 7,500 words, which was screened to find the ones that indicated possible solution paths. The selected words were classified into fourteen categories, including the three proposed originally, totaling around 130 keywords. Due to the single word limitation of our analysis software, classifying the documents by only looking at the occurrences would have resulted in a large amount of documents belonging to almost all the categories. To avoid this situation, the documents were classified only into the two categories in which they had the most amount of occurrences. The main results, ranked by documents per category as shown in Fig. 5, are described next:

- Model: In this category, the main word was again the original search term *model*, most likely due to the ambiguity and commonality with which it can be used. Other interesting result were *MBE (Model-based Engineering)*, *MBSE (Model-based Systems Engineering), MDE/MDA (Model-driven Engineering/Architecture), UML (Unified Modeling Lanaguage)* and *SysML (Systems Modeling Language)*, along with other *modeling languages extensions*. Most of the documents belong to this type, which shows great interest from the researchers .
- System: The top words found were *function, requirement, architecture, state, behavior* and *property*, etc. Crowder et al [5] note that the system architecture is utilized in a project's organization to integrate people, technology, and information resources.
- Knowledge: In this case, the terms *port, OWL (Web Ontology Language), ontology, agent, constraint, parameter, interface, pattern,* among others, were found. This variety of words shows a higher diversity in the terminology used to refer to knowledge approaches. This is expected because the literature found came from various fields such as software engineering, cognitive engineering, business management, etc.
- Process: The main keywords here were, not surprisingly, the original terms *method* and *process*; however, we found other synonyms such as *technique, sequences, workflow*, etc. We also found specific methods/guidelines, such as the *V-model, IDEF (Integration DEFinition), Arcadia (ARChitecture Analysis and Design Integrated Approach), VDM (Vienna Development Method), VDI (-2206), SIMILAR (State, Investigate, Model, Integrate, Launch, Assess and Re-evaluate), FBS (function-state-behavior), RFLP (Requirements, Functional, Logical, Physical),* among others.
- Product information: This category shows that much focus has been put to the study of the product management and lifecycle approaches. Findings include the terms *PLE (Product Lifecycle Engineering), PLM (Product Lifecycle Management), lifecycle, PPO (Product, Process, Organization)* and *CPM (Core Product Model)*.
- Simulation: The found keywords here include *simulation, Simulink, Matlab* and *SimuUML*.
- Contexts: This category's aim was to map the distinct contexts in which integration would be relevant. Results included *Cyber-physical Systems (CPS), System of Systems (SoS), Product-service Systems (PSS)* and *Mechatronics*, among others. All these areas require integration of many disciplines and are relatively new trends.
- Organization: For the organizational approaches, the top terms were *communication* and *standards,* which are general. Nonetheless, more specific terms such as *concurrent* and *collaborative engineering* were found as well.
- Solution characteristics: The goal of this category was to find relevant terms that describe properties considered important in the context of integration. The top words found were *modularity, reusability, consistency, traceability* and *interoperability*.
- Tool: The two main mentions found in this general category are *tool* and *workbench*.
- Matrix: This category consists of a distinct path based on *matrices* known as *DSM (Design structure matrix)*. While, a large number of papers within our query did not address it, it corresponded to the highest cited paper in our set.
- Specification languages/standards [1] : With this category, we wanted to map other types of languages, apart from modeling, that were being used for communication. The most prominent results are *STEP (Standard for the Exchange of Product model data), XML (eXtensible Markup Language), DSLs (Domain Specific Languages)* and *VHDL (VHSIC Hardware Description Language)/VHDL-ams*.
- Framework: This general category aimed to map the different frameworks proposed as solutions. Interesting words found here are *framework*, *DoDAF (Department of Defense Architecture*

[1] *The resulting number of documents for this category is too small, so in the graph it is not clearly visible.*

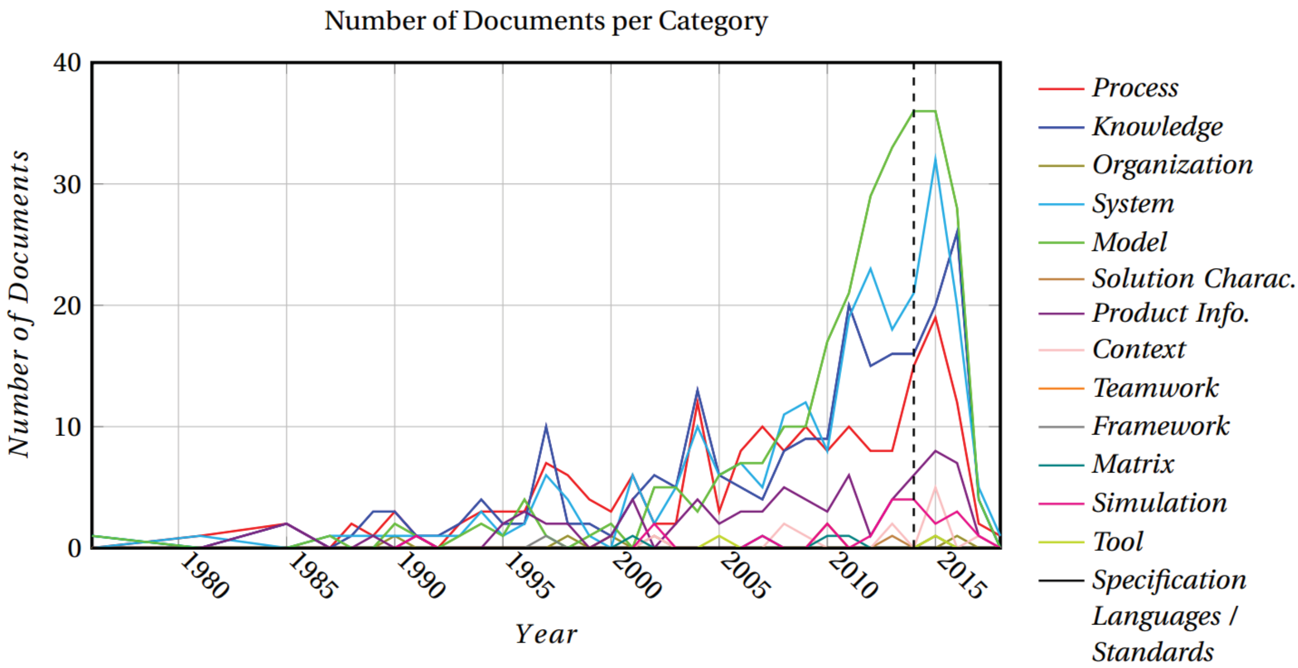

Fig. 5. Number of documents per proposed category.

Framework) and MoDAF (*British Ministry of Defence Architecture Framework*).

- Teamwork: The objective was to find out which term was more widespread to refer to multiple disciplines, as it was one of the problems encountered during the initial search. The words *multidisciplinary* and *interdisciplinary* were the most popular.

The fact that most of these categories could seem very elementary and greatly human-relatable can be explained by the fact that the need to integrate the work of two or more people stems from very fundamental principles of systems engineering, human psychology and human existence [20]. Grady [20] points out that human limitations, i.e. the fact that we can only know, process and master a limited amount of information and technologies, are what actually drives integration. It is, in fact, the humanness of the topic that makes it so interesting, yet challenging.

V. Limitations of the Study

The main limitation concerned the automatic word-list generation software (Atlas.ti 8©), because it only identified single words, i.e. no expressions, which could have caused loss of context. Common expressions, such as MBSE, were identified by acronyms, which could have triggered some occurrences that were part of a larger word and not an acronym itself. In spite of this, for each keyword proposed, we found references to the correct concept, so we consider the quality of the identification to be satisfactory.

VI. Conclusions and Future Work

The initial literature search attempt of the authors proved how difficult it was to find relevant publications for the topic of integration of multiple disciplines in the context of systems/products design. To tackle this problem, we proposed an organizational point-of-view approach based on a classification of process, knowledge, and model concepts. This initial search query resulted in 3492 hits, which were narrowed down by applying a relevance and theme criteria. The final selection included 1023 papers, resulting in a very diverse and representative set, which had not been possible at first. From the maturity assessment performed on this set, we concluded that the research area is still at its infancy. This was due to the type of outlets, which in the last years were mainly conference papers not yet matured into journal papers and the fact that the testing in the publications is prominently based on cases and examples and less on industrial applications. Another main contribution offered by this paper is a set of highly relevant keywords (~130) grouped into 14 categories, all of which clearly indicate paths to possible solutions. These identified keywords constitute a solid guideline that will further support our search for meaningful papers concerned with the problem of integration in the multidisciplinary design context. Therefore, our next step is to use the current paper selection to create a much needed in-depth literature review. Our end goal is to identify, among others, which disciplines and design phases are being integrated, and what are the limitations of the current approaches. In this future review, the limitation of the current set to the Scopus database will be tackled by using techniques such as snowballing, which will lead to other databases and industrial sources. The continuation of this work will result in a comprehensive analysis and evaluation of the state-of-the-art and a critical identification of the most promising research directions.

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