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LESSONS LEARNED FROM R&D EXPERIENCE AS GUIDANCE FOR COACHING AND DEVELOPING ENGINEERING TALENT

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Abstract. *This paper aims to share expertise acquired from industrial R&D environments, regarding directions to how engineering talent can better exercise their skills and abilities with eyesight towards gathering insight and creating confidence about a developing product. The following generic design tasks are reviewed regarding the state-of-the-art on how they are carried out: modelling and experimentation, communication and prototyping, and verification and validation. This paper draws insight from the authors' experience through two industrial case studies carried out in different positions: one as observer, other as practitioner. The lessons hereby presented were drawn from observing how the processes went through about experimenting with conceptual and detailed design specifications; these are described in terms of principles to design practice and on how these shall inform the formation and development of mechanical engineering students as talent for the future.*

Keywords: *Design practice, Mechanical design, Communication*

1. INTRODUCTION

Knowledge about the engineering design process has been evolving since the late XX Century, with an eye to formalisation and structure: the degree of detail to which it is being characterised since the early 2000's is becoming better applicable to a computerised understanding of the designed product and its practice. As advanced computer systems can incorporate systematic design models to the degree of design reasoning, this is opening an opportunity to shift engineering design education towards a more fluid and informal understanding of how design methods work among people. In this line of sight, the role of engineering design practice into enabling confidence that a solution will succeed to its design specifications is a relevant harbinger to a successful commercialisation in the market at large.

Many core sources of engineering design knowledge refer to the design process as a way through discovering what will work, and how it will, towards the satisfaction of a need. The how part is supported by having people investing their skills and abilities into first making something and then seeing how it works. This is clearly addressed in Booker's definition of designing as recalled by (Hubka & Eder, 1992): "Simulating what we want to make (or do) before we make (or do) it as many times may be necessary to feel confident in the final result." While the trait of figuring out the way something works has always received a good lot of attention from the community, the focus of the academic community must change a good deal from a pure analytic approach to a creative-experimental approach.

This paper aims to characterize lessons learned from practice in industrial R&D environments as principles that designers should apply in their practice to learn and execute practices of design and experimentation. Drawn from field expertise, these principles could - for instance - be used either to develop an engineered concept or to validate a final design as intended product. The experience through both engagements yielded insight about how the industry context influences the needs of knowledge towards choice and validation in mechanical design, and how these directions influence the acquisition of knowledge through the design/experimentation process

2. BACKGROUND

Knowledge gaps are part of life when it comes to engineering design practice, and engineering talent should understand how to use the best of their skills and abilities to get their solution to work. In attention to this, this paper aims to discuss principles to teach and develop engineering talent in academia within a creative-experimental approach by focusing the exploration and discovery aspects of engineering, based on lessons learned from R&D practice through different phases of the engineering design process. This section will introduce the following subjects as background to the subject of this paper: modelling of assumptions and solutions, communication of solution and performance approaches, and verification and validation of the final design.

Modelling of assumptions and solutions: Since early on through the design process, renderings and prototypes reveal emerging properties of the design, which enables designers to steer the course of shaping design characteristics towards lifecycle design requirements (Menold et al., 2017). These are seen to attract collective attention into how a new product or system can work: prototyping is mostly associated with communication about the developing product (Camburn et al., 2017). Organisations often choose computational models over physical ones as they can, as the latter may be expensive to build. Designers need to ensure the validity of engineering models in basic operating modes to build up confidence (Savoie & Frey, 2012). This does greatly help the engineering design process towards reaching solution maturity as valid models help verify the design with shortcutting physical models and reducing lead time (Tahera et al., 2018).

Communicating solution and performance approaches: Design methods enable useful outputs for product development goals, with resulting information being carried and communicated by design models on which parts of the design and their relations can be recognized and interpreted (Andreasen, 2011). Models are also useful to communicate impressions (look-like) on their intended appearance and/or as means to (work-like) render functions of a solution alternative (Ulrich & Eppinger, 2003). The engineering design process is characterised by a search for solutions; here, early problem-solving - front-loading - seeks to anticipate design issues to earlier phases of product development (Thomke & Fujimoto, 2003). Because solution lifecycle factors will determine the emergence of more issues, the not-so-careful anticipation of issues may short-cut concept development and miss the ability to control impacts from changes (Fixson & Marion, 2012).

Verifying and validating the final design: The validation of solutions may be firstly carried out with testing functional models about specific requirements - such as optimized performance, avoidance of failure, or reduction of variation (Wu & Hamada, 2009); and then, through executing an experiment-based verification and validation (qualification) program that authenticates product performance against the likely operational conditions of the solution (Det Norske Veritas, 2012). As the design team gets the product design to a degree of confidence that requirements and standards can be met, the development focus shifts to planning the validation of a final design through a test program (Buede & Miller, 2016). Such test programs involve submitting specimens of the product design (partial or whole) to one or more pre-selected environments according to standards and regulations (Ye et al., 2017).

3. RESEARCH APPROACH

This paper presents insight collected through both collaborative academic study and professional practice, thus following an overall case study approach (Yin, 1994) in two cases. These are performed with companies in the sectors of medical devices and offshore oil and gas structures, respectively, where this account takes insight from positioning of the author in both observational and active roles in engineering and development practice.

The medical device case study (Marini et al., 2011) has been developed as a longitudinal study following the early development stages of a new product. The offshore oil & gas structure study (Marini & Pitella, 2017) has been developed as action research following the qualification of new structural designs from a new-built factory. With specifics reserved to each original study, the lessons learned from experience in both processes are hereby discussed to yield guidance for the formation of new engineers.

The medical device case study (Marini et al., 2011) has been developed as a longitudinal study following the early development stages of a new product, which did not proceed to launch yet had features incorporated into currently available products. The study followed the early design phases, under which 20 (twenty) concept alternatives were generated. The investigation focused the evaluation and selection of alternatives through the concept development process, looking at the design input that was generated for the following purposes: to enable the verification of developing designs, and to evaluate the feedback regarding the correction of design flaws in rejected alternatives.

The offshore oil & gas structure study (Marini & Pitella, 2017) has been developed as action research following the qualification of new structural designs for subsea products that were produced from a new-built factory; these designs are based on industry-wide design codes with proprietary technology regarding the materials and geometries to which the structure parts are made. The study followed the prototype testing phase through the qualification of different applications being produced for operation in deep waters, with an eye on knowledge acquisition towards developing engineering competence and expertise in the local unit.

These experiences play into building insight about the different possible ways to acquire knowledge through prototyping and experimentation in the design process. More specifically, this paper characterises principles to knowledge acquisition that took place in the design processes through both cases: during concept development, a divergence/convergence process is carried out through which an engineering solution is selected among several alternatives; and, during detailed design, a verification/validation process is carried out through which an already developed engineering solution is tested and validated to lifecycle requirements in different applications.

With specific methodologies reserved to each original study, this work is intended to propose principles to capturing knowledge from engineering design work with basis on experience on both processes. Hence, this study takes on a retrospective character to be a descriptive study (Blessing & Chakrabarti, 2007) about how engineering knowledge can be acquired from practice, benefitting from the position of the author in both observational and active roles.

4. RESULTS AND DISCUSSION

The lessons learned from experience with engineering R&D in both case studies are hereby expressed in terms of principles to practice for consideration in teaching and preparing new engineering talent.

Draw a design roadmap: the first lesson from undertaking the cases is considering the way ahead to develop and validate a given design, with basis on the following aspects: taking the scope and purpose of the job into account to make and verify the solution in a systematic way; and, considering the interests and characteristics of people and environments to plan how, when and whom to interact with and drive the task to its completion.

The ability by design teams to proceed throughout the design-build-test-analyse steps of the experimentation process requires engineers to formulate and communicate the way forward to designing in its different aspects. The medical device case involved the formulation of concepts based on working principles, which were implemented in their mechanical parts through a progressive evolution in concreteness and maturity in their prototyping and experimentation: firstly, the design team built virtual part and assembly models to implement concepts and their working principles, making preliminary performance evaluations; then, designers verified the functional feasibility of concepts by experimenting with physical mechanical models; and, finally, the team has built engineering prototypes reproducing functions and their intended embodiments through architectural and component design. These experiments performed by mechanical designers supported the evaluation of design properties such as click stiffness, displacement force and linear displacement as solution criteria.

Each step in the way involved drawing an image of the design as a structure of components and expected characteristics, which directed the acquisition of knowledge about the workings of alternatives through modelling, and the generation of design output in following that image. In the offshore structure case, designers performed pre-build assessments based on records and sources about the performance of existing products, with an evaluation of these according to the image of how the current product worked. In the medical device case, the image for pre-build assessments was composed of features, definitions carrying functions and abilities that were performed by current designs in relationship to necessary requirements for the design to succeed. Design teams evolved to virtual and physical models/prototypes after exploring variations in principles and arrangement, with basis on the part assembly of the currently commercialised design. Physical models allowed designers to figure performance parameters that were critical to satisfy the features and requirements established in the beginning of the project.

This example demonstrates the principle of drawing a design roadmap for concept design, starting out from existing assumptions about how the design is to be composed. Designers connect such concepts with purpose and functionality with basis on design process models; this facilitates the intuitive deployment of working principle and layout variations on solution alternatives to explore the way they work in actual design parameters. Yet figuring out the development path to a solution through concept development required a systematic approach to make functions, working principles and behaviour issues fully explicit. While employing such clean-sheet approach make reverse engineering effective, planning the way forward with such models makes development more accessible for the designer along his team.

Carry a toolbox and get new tools: one significant lesson from experience with the cases is the need to carry knowledge that is useful for the job with an eye to updating the ways of doing it. Here, knowing the way with engineering tools in use, means the ability to approaching a task with support of models and tools, and communicating its results about how the design is characterised. The aim here is to make sense about how to communicate and elaborate issues on how a developing design performs, thus giving support to decisions and further engagement. The offshore structure case involved an engagement with engineering and dimensioning activities that evolved to the certification of prototypes, to fulfil the required validation to project requirements: firstly, parametric structural layouts were acquired as basis for establishing prototype production specifications along with experimental procedures and specifications; then, experimental procedures were performed and analysed along with the certification body, where aspects such as manufacturing and performance variations were addressed together.

Each step in the way involved reference knowledge that provided basis to performing inquiries about structural layout characteristics, expected performance and parametric variations. The acquisition of knowledge is directed by reference knowledge ('tools') carried by the designer along the information accumulated from documents in the organisations' database. In the offshore case, engineers started the experimentation process with acquiring structural layouts to generate prototype specifications and follow on their manufacturing. This follow-up included assessing the effect of possible dimensional variations with support of expert judgment, with communication based on design tools that approached the prototype specification on its dimensional properties and their relation to design requirements. Engineers were able to perform independently thanks to growing ability and confidence about the tools on the prototype being experimented.

This example demonstrates domain knowledge and engineering tools as vocabulary whose fluency enables engineers to communicate and share design results. The evolution of engineering competence about handling design tools and their respective vocabulary enabled more effective communication into reducing ambiguity and progressing onto a successful design outcome.

Test your sense and engage in teamwork: an essential aspect of engineering work as experienced in the cases is the strength of resources engaged in a design assignment. This is benefitted by getting to share and align issues and intent and with peers and managers, which requires an ability to make sense and test it by focusing how useful and affordable it is within the objectives at stake in the team and the resources available in the budget. The testing of an engineers' sense about the design being experimented involves eliciting expert/manager viewpoints about the adequacy of one's ideas/assumptions to certain task. Experimenting and evaluating the solution is a team activity and hence designers need to do this testing within a group environment; this process is aimed at knowing together how to reach confidence to recommend a decision.

The design process in the medical device case was characterised by a 'concept race' where designers were individually in charge of developing concepts based on their ideas about mechanical functions, and their embodiment. Each resulting concept - embodied and experimented as near- or fully-functional mechanical assembly - was judged by designers about their preference. Designers engaged into qualitative assessments by grades between 0 (zero) and 5 (five). This process involved designers carrying out their work with testing their sense through building ideas and engaging in teamwork through evaluating the concepts. Designers acquired knowledge about the ways forward and the resulting workings of their concepts with basis on the reference frameworks that were available along design tools they had at their disposal, enabling them to proceed towards the engineering concept.

By the offshore structure case, this process went on towards setting prototype specifications, and this is more significant when considering the elaboration of experimental procedures and the execution of experimental analyses from those. This process took place both in the design and process aspects of the product, with basis in general frameworks: firstly, proceeding on the design aspect involved approaching the structural layout with checking correct input data, calculation approaches, and test results with their analysis; and, proceeding on the process aspect, with basis on an inspection and test plan, considered sharing the view forward, declaring the assignment to align intent and course, and delegating matters of activity logistics to stakeholders and collaborators in different units.

Both cases had designers forming their engineering sense on the product being experimented for the purpose to implementing a view on how the task could be solved: in the medical device case, it was the generation of different designs to be evaluated; in the offshore structure case, it was the proposition of experimental, inspection and measurement approaches to be executed and analysed. Yet it was about the process of tentative building and testing that supported the stacking up of critical knowledge to enable the construction of the deliverables from the design/experimentation process.

Be there and keep close to the action: notwithstanding the current focus on construction and predictive models in engineering practice, knowledge is best understood when rendered/experienced in a concrete manner. This is best achieved with witnessing and/or participating a design activity that is included in ones' assignment, where one positions him/herself around an instance of the design, and its testing/operating environment. To acquire knowledge, engineers need to engage the problems at hand, which involves a proactive pursuit of understanding about what the design is aimed at, and how this is to be achieved. Positioning oneself close to key activities in the experimental process is essential to ensuring the quality of the interaction between the designer and the subject of his work.

In the offshore structure case, the influence of manufacturing design to direct inputs or correction factors within predictive methodologies is a particularly relevant factor. Methodology designers need to grasp the experimental process and take an active role on the specification and manufacturing of prototypes, to assess the influence of product characteristics to how their predictive methodologies work. In the while the methodology designer is mostly responsible for predicting how the product will work, his activity benefits the most when collecting and analysing supportive knowledge from witnessing the manufacture of prototypes through the production line and from performing experimental and reverse engineering work as part of intended test procedures. This process involves engineers giving priority to departments and places where relevant information to their activity and skillset are defined and generated, and then moving forward and back between their own core environments and the information-generating areas. This is essential for maintaining the link where the core activity performed by engineers is founded on relevant and actual inputs, thereby ensuring validity and legitimacy of the engineering output.

The medical device case has employed a set-based development approach with several concepts being fully developed to physical testing models, with integration between mechanical and electronic models; the project involved an engineering team including different specialties, such as mechanical design, electronics design and manufacturing/assembly design. An example of cross-interaction took place where manufacturing/assembly engineers had access to the development of mechanical and electronic components and then were able to propose assembly and modularity refinements to the final concept. Both cases involved the practice by engineers of pursuing knowledge about factors influencing their activity besides their core job, which was beneficial to their building more accurate picture of how these factors played out on their own domain. This accuracy is obtained by engineers who participate as witnesses to activities about factors of influence to their own work, keeping a close look upon influences from other areas/specialties to their core activity in the organisation.

4.1 How does engineering expertise relate to the state-of-the-art?

Draw a design roadmap: the design roadmap is to consider the knowledge about how to make what stakeholders want. There are critical aspects engineers need to consider with favouring simple and effective work.

On the effect of the complexity/processing trade-off in structure, geometry and activity models to properly represent a path to a solution (Andreasen, 2011), it can be represented by considering two ends: in the one end, models that are too complex lack transparency to the elements that need to be recognized; in the other end, models that lack enough characterization of the solution tend to leave engineering conflicts under the rug. Engineers should be able to use modelling approaches to frame and explain their ideas with enough clarity about how the solution shall work and how its implementation is intended: modern modelling techniques still take significant effort from design teams into generating clear and explicit information about the solution (Ahmad et al., 2013). This relates to experience in which both the problem-solving activity and the solution being developed need to be characterized with a finite number of elements that are transparent to the engineer. Here, solutions that are complex over a certain degree of detail will require iterative progression, through several cycles in increasing detail, until reaching those elements considered relevant towards the cognitive workload of engineers. Here, engineering teams consciously consider them to have negligible impact to the activity and sometimes decide to live with something good enough (Eisenbart & Kleinsmann, 2017).

On the level of fidelity in models and/or prototypes about having them render the most relevant characteristics of a process or solution to stakeholders in the design process (Jensen et al., 2018), there are directions for improving the practice of representing the ways solutions are intended to work: firstly, that some compromise between prototype properties and final properties is always required to improve the feasibility of prototyping earlier, more often and on more alternatives, where simplifications such as scale adaptation, subsystem isolation, requirement relaxation play a role to reducing the cost of prototyping (Camburn et al., 2015; 2017); secondly, that prototyping should be planned and executed in a string of activities with aim at specific goals such as: achieving realisation rewards with stimulation to improvements, enabling the choice of strategic aspects to be focused on, simulating and engaging operation of and/or interaction with the solution, and allowing for flexibility of requirements to enhance the benefit of embodying the solution. From all these aims, prototypes shall inform about viability of budget and time, feasibility of functionality and performance, and desirability of attractiveness and interaction (Menold et al., 2017; 2019), with positive effects to learning, communication and decision-making in engineering organisations as prototypes carry characteristics that manifest how the actual solution may come to life (Lauff et al., 2019).

Carry a toolbox and get new tools: as the tools hereby referred work into modelling the solution before it comes live in the physical world, analysis and simulation tools need to yield comparable results to reality.

As engineers learn about tools from their course and then from their trade, they end up developing a mindset about how to solve problems, a kind of mental toolbox they acquire through their formation and job experiences. This is composed by a collection of knowledge elements about the engineering tasks at hand and their context, the phenomena and their theoretic representations, and the courses of action towards their intended results. The main issue with engineering tools and methods is the clarity to which they are shown to facilitate the solution of a problem, linked to how strong is the need for a given kind of solution: it is the context of practice that will determine the combination of tools best suited to solve engineering assignments (Andreasen, 2003). This is complemented by the issue of personal preference to certain ways of perceiving and reasoning about a problem, which will make for a selective permeability of engineers to certain engineering tools that are better suited to their motivations. The way engineers are introduced to a design task has a significant effect into determining the way the problem will be approached with, and whether they will perceive the prescribed method as matching their way of thinking. This match will ultimately determine how well engineers will perform an assignment – those people who feel a better match with the assignment and the tools they get to work with will perform to a clearer result and with better confidence on their own job (Daalhuizen et al., 2014).

Most engineering tools are implemented through algorithms that embed governing equations of a phenomenon in trying to anticipate how an intended solution might perform in real life. For the increasingly complex routines being used in engineering tools, their development and implementation is also exposed to mistakes that are seen to cause the implementation of the intended solution to underperform significantly – or even to fail. Facing this issue increasingly more often, engineers need to use fundamentals in attention to the readiness of predictive tools and methodologies in a step ahead of the design process, both to feed up their interpretations of how the engineering model works and to verify whether a current result matches past ones from experience. (Savoie & Frey, 2012). Engineering models embed a certain set of values to which they have been validated under a given procedure at certain circumstances, which may or may not be the whole universe of possibilities they may be used with. In this context, there is a two-handed dilemma that engineers face when using models to solve engineering problems: in the one hand, their accuracy to match results from known models and experimental results from reality (Oberkampf & Trucano, 2008); in the other hand, current engineering models are bound to work under the requirements, assumptions and information possessed by engineers, thus demanding engineers to be aware of the operations needed to attain expected results (Nelson, 2016). The comprehensive input requirement of current tools results in the narrow validity of calculation results, which should be augmented by engineering judgment in line with the decision being considered.

Test your sense and engage in teamwork: testing an engineers' sense requires sharing it and engaging into the teamwork conversation.

Engineering knowledge becomes actionable when it supports the crafting of conversations and dialogue onto the communication of meaning that is useful to solving a problem. The act of using knowledge can be assessed in two modes: (I) making up 'objective' positions that can be advocated for without much questioning creates the illusion of competence along the tendency of face-saving if a contradiction is caught; and (II) declaring assumptions and intent for obtaining questions and feedback about gaps and weaknesses yields supportive engagement and advice to an agreed course of action (Argyris, 1995). The context of engineering R&D is represented by design process models that mediate the connection between information and expertise towards solving a problem by using knowledge, which is two-handed in nature: coded knowledge results from a commitment of personal knowledge in terms of assumptions, skills and attitude of engineers. With focus on the dynamic of making knowledge operational within the design organisation, engineering transactions should benefit from a knowledge personalisation strategy (McMahon et al., 2004), with investing to support the embeddedness of assumptions, skills and attitudes into knowledge-sharing resources. In this context, there is an attempt to link the characteristics of task assignments and the ways people approached a task, where novices manifest traits of acquiring expertise about design assignments and thereby learning about how to approach the problem in a progressive systematic approach, whereas expert designers will act to secure guidance and gatekeeping roles through a design assignment. Meeting with experts helps stabilize and consolidate positions about design alternatives sought by novice designers (Kim et al., 2011).

This process explains the factors influencing the progress to making knowledge actionable, which requires sustained engagement with peers and leadership: firstly, about consolidating the sense of a problem-solving idea or concept regardless of ownership, secondly with collaborating towards the engineering implementation of solutions, and then to roll out the solution effort to other areas of the organisation. Thinking ahead with scenarios to ensure progress, engaging stakeholders for sustained implementation commitment, and applying empathy to think of those served and/or affected are key elements to proceeding with knowledge implementation (Austin, 2013). Regarding the personal motivation to kickstart and collaborate about innovative goals, these goals shall be made operational with knowledge that can be tested and turned into more valuable insight; this requires individuals to employ their sense into selecting relevant knowledge and ideas that will be useful in the organization and towards their marketplace. People who make a better fit to corporate values usually become more successful as professionals, and this determines the need to foster a culture of openness and legitimate interest into cooperating in engineering assignments (Albors-Garrigos et al., 2016).

Be there and keep close to the action: even in the age of teamwork in the cloud, direct participation on engineering conversations and/or witnessing an undergoing engineering task (Wu & Hamada, 2009, Buede & Miller, 2016) are essential components of awareness and expertise in practice.

These characteristics are inherent to problem-solving practice because they are mostly enabled by opportunity, which is basically an occasion at which the individual engineer recognizes things, events and actions in relationship to knowledge that can be made operational to solve problems. Here, information is acquired in relation to the mindset of the individual, who reasons about crucial aspects and possible good reasons for making preliminary decisions, thus drawing a possible way forward to deliver a solution to the standing problem (French, 1992). In engineering design, these opportunities are enabled through building, observing and experimenting with solution-conveying devices such as test rigs and sensors, prototypes, CAD assemblies, diagrams, charts, models, and so on. These are often referred to as engineering tools yet express a communication language whose meaning is to represent how a solution is intended to work; they "provide a milieu for inquisition and exploration of the whole and its interfaces within, as well serving to illustrate hard technical features or function when deployed by participants" (Bucciarelli, 2002).

By exploring and performing inquiries about the intended solution as represented by the devices above, engineers form their own strategies to dealing with issues and sharing knowledge. However, it is assumed that these devices are widely accessible; the truth is, graduates struggle to apply the theories they learned to real life. The success to implementing design strategies to concrete solutions depends on the ability to navigate between the phenomena they take part on and the theories that describe how they work. Besides, this requires the ability to link and communicate across several domains, such as solid mechanics, tribology and heat transfer. As a result, contextual detail available from experiencing design routines and interacting with senior peers creates opportunities for novice engineers to infer specialised knowledge (Wolmarans, 2016).

4.2 How are we to form and develop engineering talent?

Draw a design roadmap: there is an illusion that experts and managers will come to rookie engineers and give verbose instructions about what they should do. The use of models depends on specific contexts with focus on the intended output of the engineering activity. Achieving the full potential of engineering students involves giving them examples and guiding them to think ahead of the task with regards to experimenting and sharing. Here, the drawing of principles based on experience would enable the next-generation engineers to take helm of machine reasoning.

A reflection of the authors' own experience focuses the role of simple and clear representations as mediators of the way forward through the engineering design process. Especially at the front-end, a representation of the development process of the medical device enabled the reasoning of progressively detailed 'design images' of the solution until solution alternatives could be compared through analysis, and then iterating to synthesize common criteria approaching the architectures of solution alternatives, their components and their performance. In the offshore case, representations of how oil & gas equipment was built enabled the working of relevant dimensional and functional parameters along the predictive design methods that were available. On such practice, the industry context requires coaching of engineering talent onto kickstarting an assignment from the discussion of strategic intent and the intended level of analysis to the design assignment. Talent should be able to frame engineering tasks in a clear and stimulating way, pushing the way forward in a methodical approach with small rewarding steps.

In design practice, prototyping strategies are not straightforward as they seem: the degree of integration in the architecture of the medical device was an obstacle to subsystem isolation; the level of demand to design requirements allowed little relaxation of requirements to prototyping oil & gas equipment. Academia could well recognize the iterative and progressive character of implementation tasks (prototyping, for instance) in intermediate steps – affordable and rewarding – to clarify how a solution is intended to work. Evolution to support knowledge-building towards choice and validation of alternative designs would play out in two ways: by using top-level and intermediate models as means of setting up and/or discovering properties of the intended solution; and by demonstrating how these models work in support to building intermediate-level prototypes that demonstrate the workings, advantages, or shortcomings in a solution. Engineering formations need to organise courses and assignments through an iterative approach so that engineering talent can learn the practice of solution-building through using process models as guidance, and then use progressively concrete engineering models as tools for understanding how the solution performs.

Carry a toolbox and get new tools: the matter here is about the accessibility of engineers to the tools of their trade: some of them are readily accessible at little or no cost and others are proprietary inside the companies. Therefore, engineering talent should be equipped with the basics that enable them to succeed, such as: fundamental scientific basis, math and coding skills, open-source engineering tools. Their teaching should take requirements of the practical context into consideration, with matters like cost, complexity, risk, trade-offs being demonstrated through real-life examples.

The matching between engineers and tools in use has, by the least, the following effects: in the one hand, favouring people whose attitude and reasoning match the way the trade is done with engineering tools at its centre; in the other hand, calling attention on the need for companies to use engineering tools that match the reasoning developed by the new generations of engineers. The learnings from both case studies enable a reflection about how industry organisations favour tools and methodologies that deal more closely with product properties, to the point that some teams may even use custom engineering tools; as a result, engineering practice will entail the use of a different subset of methodologies and tools than those advocated in academia. Nevertheless, engineering fundamentals with demonstrated relationship to the context and characteristics of industry solutions remain tools of trade as bases for engaging more advanced and focused engineering tools to understand the criteria to choose and validate engineering solutions.

As consequence of this, two opportunities can be considered to enhance the knowledge-building of new engineers: firstly, to augment engineering knowledge in courses with drawing application contexts for engineering fundamentals along practical expertise; and then, to push students themselves to acquire expertise in direct contact with the field as mechanism to learning the relevant engineering tools. Capturing such strategic knowledge would direct research and teaching activities toward fundamentals and tools that are better suited to the needs of the time. In a productivity context, the opportunities to automate analytical calculations and extract valuable data and program the generation of engineering reports to save on time, among others, are enabled by software and engineering tools that are more flexible to the thinking of new engineers. The use of such flexible tools should be directed by a dialogue within the engineering community about, what sort of knowledge is productive and operational.

Test your sense and engage in teamwork: an often-neglected aspect of engineering courses is the "world" that is forming around engineering talent undertaking them. It is about time for institutions to focus on a hands-on perspective about coaching students to pursue, take ownership and make use of engineering knowledge to their purposes in life. This should be done by encouraging students to test their view during classes and through assignments – by allotting certain time for focused discussion or setting teamwork assignments about people, places, tools and media.

While one single person can think of a problem and imaginatively devise a solution through using engineering knowledge in an idea, its practical implementation takes place through sharing and making it operational along several people, often with different backgrounds. As a fundamental to using engineering knowledge, communication is often taken for granted; many disciplines are taught under the assumption that the calculations they involve and require are self-explanatory. While it seems easier to focus at the core language of subjects without extras under the assumption that all engineers understand similar language, the issue is that engineering knowledge is made operational (actionable) through its sharing and use in conversation and teamwork. The problem is, conversations entail natural language in complement to the formulations; besides solving the formulae, the industrial context requires demonstrate how engineering solutions effectively perform to figure out about the choice of designs that provide good solutions.

Engineering subjects would benefit from an emphasis on how to communicate the fundamentals and make them operational towards solving a problem along peers and higher-ups in organisational structures. This dialogue should be infused into the *modus operandi* of new engineers, by learning how practitioners solve engineering problems with consulting them about how they understand it. The aim is to expand the learning process of new engineers on through their courses, by complementing the engineering knowledge from solving exercises in engineering subjects with the anticipation of engineering expertise through coaching by teachers and dialogue with senior practitioners. Extra-classroom project assignments work as 'springboards' for this kind of action as they require a teamwork organisation to implement the necessary tasks, with support of teachers and practitioners in academic institutions. Yet they require strong commitment to resources in form of labs and facilities, and thus reach only a part of the student community; new talent would benefit from opportunities to solve small problems in the field in collaboration with companies, thus entering goal-based dialogues to use engineering knowledge in problem-solving activities.

<u>Be there and keep close to the action</u>: the engineering students of today are equipped with devices that give them unprecedented access to spaces for content sharing and discussion. However, content alone does not solve the need to get hold of knowledge for their use when engaging on practice – be it during the engineering course or after. Professionals in academia should help students to take ownership of knowledge through guiding them to observe and interpret real-life situations, first through media and then by being present at specific events in laboratory or field tests.

A transition is necessary for engineering teaching, which departs from the current classroom-based model of engineering course towards a sort of 'engineering-on-the-street' approach; engineering talent shall enter contact with problems in the field and thus perceive the need to align understanding and coordinate resources for implementing a solution. The industry context relates to the ways of people in the sense that engineering students greatly benefit from having early access to field problems, through which they get a closer view onto problems requiring knowledge and attitude as developed through engineering courses; academia should take a closer look into opening opportunities for such assignments within the engineering curriculum. In most of the cases, unfortunately, the academic environment cannot really emulate a problem-solving dynamic like it works in industry; a few exceptions can be found where research groups make investigations and discover results that can be implemented in form of embodied solutions.

Solving this will require a closer integration between academia and industry actors; this will require that the benefits of such collaborations are made clear for both sides, thus drawing interest into engaging such initiatives as driven by the results that can be attained together. This integration should open problem-solving environments to engineering talent as means of: firstly, providing context to engineering knowledge so that the acquisition of expertise is somehow anticipated; and then, testing how they learn and apply such combination of knowledge and expertise in practice. By focusing the instrumentalization of knowledge as means to develop and implement solutions, the opening of field opportunities enables the link between theory and practice that is often missed by academia. Mechanisms such as rotation between attendance of course subjects and internship in practice environments should be explored by academia and industry together to enable talent to move around between knowledge-building and problem-solving contexts.

To enable talent to take progressive responsibilities on the development and choice of better engineering solutions complemented by validation of this kind of choice, the main goal of the principles above should be the anticipation of expertise-building activities in engineering course. This could be achieved by having students to carry out practice-and-field-oriented assignments inside engineering courses or by opening opportunities for small engineering tasks inside engineering companies through short-time internships. This anticipation is to be enabled by fostering an interchange between theory and practice through getting talent to move along under these principles during their formation. While consolidated theory-practice frameworks such as CDIO (Crawley et al., 2007) are available as guidance to engineering education, the progress of talent into learning these principles should be planned with consideration to the resources and contacts in between academic institutions and closely located industry organisations. Through the principles advocated in this paper, models, tools, strategies and presence are elements that work together in an engineering context and therefore cannot be developed in isolation from each other.

This motivates the need for a holistic approach to how these skills can be developed through the engineering curriculum, and the need for dialogue and integration between the parties interested in the formation of new talent. Creating opportunities for the interchange between theoretical and practical contexts should be made priority matter for both academia and industry to contribute together: academia with providing fundamentals, coaching about how to use knowledge and providing freedom to explore problem-solving opportunities in the field; industry with delegating problems, setting goals about what needs to be done and providing logistics and execution support for these tasks. The meeting of institutions and organisations should be enabled by the formation of communities of interest through informal and formal channels, such as the maintenance of network contacts, the performance of reciprocal visits, and the promotion of networking and discussion events approaching themes of interest to theory and practice of engineering. The building of knowledge along expertise will generate game-changing capabilities to get new talent to reflect on the issues of their time and come up with innovative solutions.

5. CONCLUSIONS

This paper reflects about the reality of engineering and design work being less about formulations, or boxes and arrows, yet more about how to understand and pull together innovative ideas onto useful and valuable solutions.

It is intended as a resource for people who are interested in coaching engineering students and novice designers onto learning the ways of the trade when taking about the engineering design process and the knowledge associated with it. The lessons learned from experience with engineering R&D in both case studies are hereby expressed in ter ms of principles to practice that shall be considered for teaching and preparing new engineering talent for the tasks of their profession.

As a result, four principles to knowledge acquisition resulted, with focus on how engineering talent can harness engineering knowledge to better engage their activities in industrial organisations. These principles result from the reflection of the author's experience on through the execution of R&D activities contextualised in advanced research and professional practice. Notwithstanding the incoming changes about new engineering tools and methods along the appearance of increasingly automated reasoning algorithms, the guidelines presented in this paper demonstrate a practice-oriented way forward for professionals in academia to prepare their students for the challenges of tomorrow.

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