Engineering For Social Change
A. Cooper et al. (Eds.)

doi:10.3233/ATDE240869

Revisiting the Philosophical Issues in the Practice of Engineering Design

David ANDREWS[1]
Marine Research Group, Mechanical Engineering Department, University College London, United Kingdom

Abstract. The Royal Academy of Engineering held a series of seminars on the Philosophy of Engineering in 2007, to which this author contributed a paper entitled “Philosophical Issues in the Practice of Engineering Design”. This considered this essential feature of engineering, which is to apply scientific methods to produce products created to meet human needs by ensuring their realisation obey relevant theories to achieve practical ends. This is done by a design practice which has not received the same level of philosophical enquiry that has been addressed to the pure or “natural” sciences or even engineering analysis and the research associated with that practice. While the 2007 paper is reviewed in the light of almost two decades of further research into the most demanding of engineering design practice – that of physically large and complex systems (exemplified by certain marine vessels, large civil engineering constructions and major chemical plant) – it has been observed that the practice of such design has itself grown in complexity. From considerations of design philosophy, including quite contrary visions, design at this demanding level encompasses the creation of not just technological products but also organisations, processes, environments and even ways of thinking. Thus, the practice of engineering design is very much a human endeavour that is largely conducted by teams of engineers, often of different sub-disciplines interacting with non-engineering stakeholders. With the onset of AI and Machine Learning how this Computer Aided Design practice is likely to change is seen as a philosophical and sociological question.

Keywords. Engineering design, philosophy, CAD, Transdisciplinary engineering, Machine Learning

Introduction

It was the contention of the author’s paper presented in 2007 [1] that it is largely the design element that distinguishes engineering as an activity from the ‘pure sciences’. That earlier paper was a contribution to one of several seminars on the Philosophy of Engineering held by the Royal Academy of Engineering [2]. Clearly, there is both art and science in engineering practice and the philosophical implications are worth revisiting almost two decades on, given advances in engineering practice, especially developments in Artifical Intelligence (AI).

The paper asks how the practice of (engineering) design differs from the practice of science and whether insights drawing on the philosophy of science are therefore worthwhile, or a better model is provided by the more diffuse philosophical issues arising from design practice. In part, the issue with engineering design practice is its

[1] Corresponding Author, Email: d.andrews@ucl.ac.uk.

ever-increasing scope, beyond just the engineering sciences, together with a belated recognition that engineering design needs to cover wider issues, including human factors and societal drivers, not least in the need to address sustainability when designing any complex system. This leads on to consideration of essentially philosophical issues associated with the practice of engineering design and from these issues the paper ends with a second question regarding a justification for a distinct philosophy of engineering design to assist in addressing the societal, sustainable, and potential AI demands on future engineering designers.

1. The Nature of Engineering Design

The practice of engineering design draws both on the various disciplines in engineering and an understanding of design. Much of the affinity of engineering to science (with its well-established philosophy of science) lies in the practical application of scientific insights, which have been obtained, at least initially, to better explain the physical world. Whereas, design is a more diverse human endeavour, with a less developed philosophical view (see Galle's summary [3]). The application of science to engineering – often called the engineering sciences – is used to undertake the particular activity that is engineering design, and this makes it quite distinct from other design practices.

When using the engineering sciences, engineering designers do not do so in the same manner as would a scientist. Engineers are pragmatists, wanting sufficient answers to best progress their designs, so they often employ scientifically informed but scientifically unjustifiable assumptions and further simplifications. This is justified in the pragmatic sense of getting a hopefully workable solution to the task in hand, in order to progress a new design project.

The other aspect of engineering design that is different to the sciences and designers use of the engineering sciences, is that which is often said to characterise engineering design, namely its creative nature. Often practitioners see creative design as confined, in engineering, to the conceptual creation or early synthesis phase of designing a solution. So once the design's essential form has been created, in a divergent or often brainstorming manner, the rest of the design process is seen by many engineers to be more rational, scientific and convergent. It is then that the engineering sciences can be fully applied to analyse the new concept for its technical feasibility and evaluate the results of that analysis to make decisions on what is acceptable in the new design and how it should progress. Ferguson [4], in Engineering and the Mind's Eye, seems to counter this by pointing out that, throughout the process of designing an artifact, engineering designers make dozens of small decisions and hundreds of tiny ones. So, creativity is a very difficult issue and not just engineering based designers are very wary of trying to pin it down, almost for fear of destroying what is often considered to be some kind of 'magical' element. Whether this continues to apply three decades after Ferguson's view with the current extent of CAD in engineering design and further AI initiatives seems open to debate?

2. How does engineering design differ from the practice of science?

There appear to be two aspects in which the design element in engineering practice is significantly different from the use of the scientific method in engineering analysis. The first applies specifically to engineering design as a field of engineering practice and this practice extends far beyond the direct application of science (by which is meant the classical physical sciences) to those many other disciplines, such as economics, law and ergonomics. These non-engineering disciplines can be intimately involved in producing the product of the engineering design process, such that the practice can be seen to be trans-disciplinary.

Many engineering design issues are associated with the human application of the designed product and are crucially important in the decision making that essentially constitutes "doing design" [1]. These issues include economical drivers as well as societal pressures and constraints which can be legal, ethical, cultural, and political, as well as direct ergonomic and psychological impacts. All these factors mean that the engineering designer has to be much more than just an applied physical scientist. They therefore should be at least aware of the human sciences and the other topics, all of which require ever greater breadth in the engineering designer's knowledge base, while all the time that broader knowledge has to expand alongside the growth in the direct technological fields.

The second aspect is that links engineering design to the wider practice of design is an issue with which many engineers have difficulty, namely that of the aesthetics of the artefact being created. Aesthetics may appear subjective and not very appropriate to a scientifically based discipline. The wider endeavour of visually led design, which ranges from architecture through to graphic design, sees aesthetics as a key aspect. It has been quite a fruitful area of philosophical or at least methodological investigation, since the early 1960s and certain engineering designers have contributed significantly to the field of general design research, which could be said to have been started in 1966 by the chemical engineer Gregory editing "The Design Method" [5].

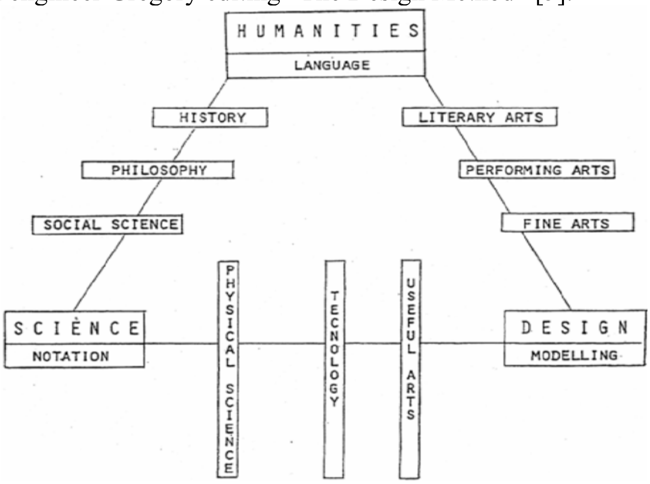

Figure 1. Bruce Archer's Representation of Design as the Third Culture [6]

As part of the early debate on design practice, a particular view was put forward in 1979 by the, then, Professor of Design at the Royal College of Art, Bruce Archer [6], who saw design as a third culture, alongside the humanities and science, see Figure 1. There he showed design – not engineering design, but design – with modelling as its means of communication, as distinct from language, for the humanities, and notation, for the sciences. Archer's diagram is open to debate, but it can be argued that engineering design (rather than his term technology) should be placed at the centre of his triangle, and possibly uniquely so, since it requires not just visual design models, that he identified, and mathematically based science, but also language. If engineering design is being adequately practised, the designer must be adept at all three of these means of human communication.

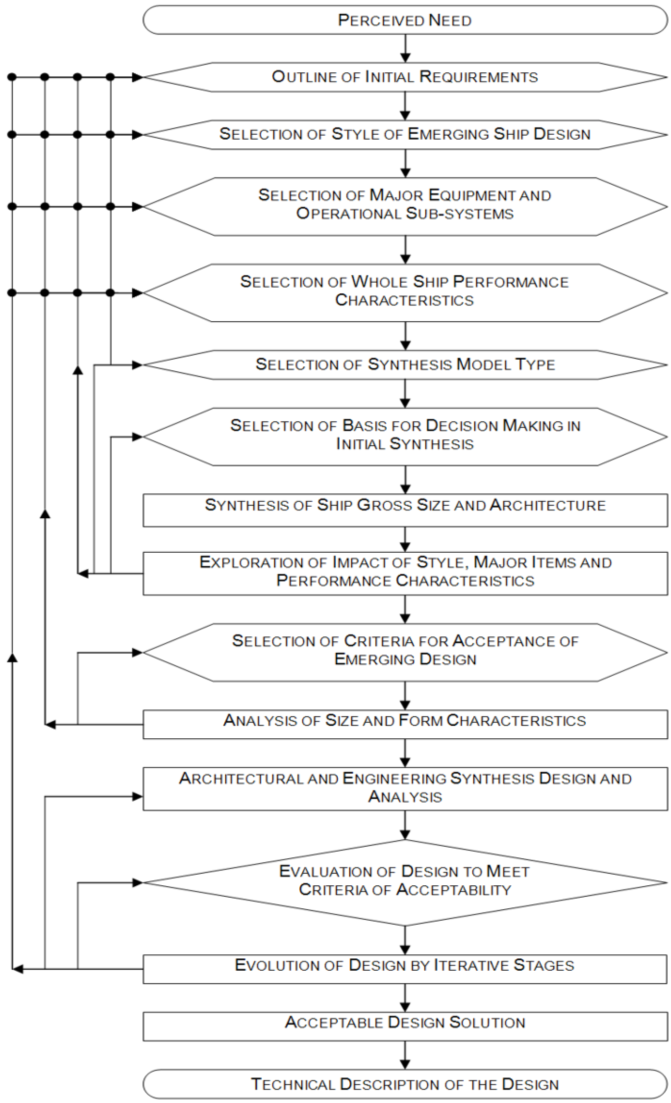

Figure 2. Representation of the Overall Design Process for PL&C Systems Emphasising Key Decisions. More detail at [10]

The author, when a senior designer/project manager of large-scale projects, spent most of his career writing to manage the wider issues of such projects, rather than directly doing engineering science, as required in the earlier part of being an engineering designer. From Archer's diagram, design is communicated by language and by notations, to undertake scientific analyses, and to create models. Engineers also use visual representations to describe the design process. In another of the 2007 RAEng seminars, Lipton [7] a philosopher of science, pointed out that even when talking of the scientific method such philosophers do so using verbal language, or occasionally logic notation, whereas design methodologists usually produce diagrams to explain the design process. This is done not so much to explain how design is performed (pace Ferguson's remark flagged up earlier) but rather to describe the process one appears to undertake in designing something. The author is a ship and submarine designer where, in teaching ship design to naval architectural students, the profession has been wedded to describing the process of ship design using the design spiral [8]. This usage has been adopted largely due to it showing the iterative nature of the process in arriving at an engineeringly balanced solution.

However, as a practitioner and researcher at the most complex end of marine design practice that of naval vessels, the author considers the design spiral to be an unrealistic model of that practice [9]. For many years, before ending up in academia, the author propounded a strategic level representation of the design of complex vessels emphasising decision-making as the basis for describing the process. It is relevant that all too often ship designers often make key decisions by default or even without question. This is shown in Figure 2, taken from [10], where each step is described in some detail.

Figure 2 distinguishes decisions or selections (in hexagonal boxes) made by the designer from design activities or actions (in rectangular boxes), which cannot sensibly be undertaken without the, at least implicit, prior decision being made. The important thing is that this is part and parcel of the design activity that most descriptions of the engineering design process fail to acknowledge and thereby implying the process can be readily automated. This implication has grave consequences as it can curtail the necessary exploration of creative design options [10] and with Computer Aided Design (CAD) ubiquitous in engineering design and beyond, has the further result of closing down the human designer's influence on the design. Thus, the design becomes more opaque and constrained by limitations imposed by the CAD software team or by an AI driven CAD system. Two further remarks about Figure 2: firstly, it shows a large degree of recycling or reconsideration of both the key decisions and the associated activities in the light of progressing the design and undertaking the overall aim of early-stage design of PL&C systems, which has been identified as 'requirements elucidation' [10; 11]; secondly, the most important step in the strategic design process is the selection of the style of any specific design option. The latter can be seen as part of arriving at a design description and a matching set of requirements, together the basis of proceeding to the rest of the design process - indicated in Figure 2 by the last three steps.

3. The wide scope of engineering practice

In any philosophical or methodological analysis of engineering design, it is important to point out that there is an immense range of design practice under the umbrella of engineering design. Often textbooks on engineering design, in describing engineering design in general, refer to the design of engineering components. In a way this is reasonable, given that larger and more complex engineering products themselves consist of such components, usually as a part of sub-systems providing specific capabilities to the overall system [12]. However, any representation of the design process for mass-produced components or small engineering products, manufactured in very large quantities, is inappropriate for the designing of the other extreme of engineering practice. The latter has already been identified as design for physically large and complex (PL&C) systems that are "bespoke" or made to order, rather than purchased from a production line. Such products include automobiles, rail stock and even aircraft, all of which commence manufacture after several physical prototypes have been extensively tested (often to destruction).

A modern version of non-prototype, one off complexity could be the design of software for major engineering projects, including for aircraft, power stations and large-scale communications, command and control systems. Although very aware, from managing naval ship projects, of the significance of software development in project risk management ("it always goes wrong"), the author has regarded software design as the prime justification for adopting a "hard" systems engineering approach in engineering design. Yet even this was challenged by Coyne's assertion, from an IT stance, that there are no formulaic theories of design, just generalisations [13]. This would seem to undermine not just systems engineering but also the endeavours of the design methodologists, as does Coyne's championing of metaphor over models as the basis of design [13]. Furthermore, some software engineers wish to replace "classic" systems engineering with Systems Architecture [14], which saw the naval architect's ship design practice as the model for the better design management of very large scale (often safety critical) software production from concept to acceptance. Parallels have been drawn between PL&C systems design and large-scale software design [15].

Because PL&C products are relatively few and each immensely expensive, they tend to be produced for long usage and hence adaptability often figures as a design objective, as can multifunctional usage. Thus, at the front-end of the design process, without the comfort blanket of a prototype, working out what is wanted and what is affordable can be demanding. Urban design theorists coined, 'the wicked problem', to encapsulate this issue, so that determining the right balance of requirements can be more challenging than the subsequent designing to meet those emergent requirements [16].

The "wicked problem" aspect distinguishes the design of such complex products from the many descriptions of the design method that start off with a clear need or set of requirements, often with the client starting a bidding process. A preferable approach for complex designs, in response to the 'wicked problem', is to focus the initial phase on elucidating the requirements. That is a trial-and-error dialogue between the designer, producing prospective solutions (and the plural is very important here), and the customer/requirements owner/end-user, such that both are involved in trying to reveal what is really wanted and achievable [10]. The biggest customer for UK industry, the UK Ministry of Defence, seems to have forgotten this prime role in a naïve desire to pass all the design risk to its suppliers, despite the US Navy recognising the error of this approach when the then US Secretary for the Navy decidedly rejected this mindset [17].

Given the design of complex large-scale products has these distinct characteristics, this high-end engineering design, also, presents the designer with a range of design synthesis choices, which is driven by the degree of novelty, as shown by Table 1 taken from [18]. The table shows that the complexity of the process can range from simple modifications of an existing product, through to both radical configurations, largely adopting the current technology but rarely attempted due to the risk of unknowns (without the prototype), and then even more rarely, radical technological solutions. These latter have to be designed in a manner much more akin to aerospace practice than the bespoke approach to bridges and ships, both in requiring vast development costs (including prototypes) and the need to design and build specific tooling and manufacturing facilities. This means any attempt to systematise engineering design practice must at least recognise that there is this spectrum, from component design right through to a range of choices driven by the degree of novelty in the solutions to be explored with designing complex systems.

Table 1. Complex design categorised by increasing design novelty [18].

Synthesis Type	Example
second batch	A stretched Airbus
simple type ship	Most commercial vessels
evolutionary design	The three generations of recent UK nuclear submarines
simple synthesis	UK Type 23 RN Frigate concepts
architectural synthesis	UCL Mothership studies
radical configuration	The London Millennium Bridge
radical technology	The Space Station

4. Some philosophical issues in engineering design

The first of the methodological or philosophical issues suggested when considering, at least large and complex products, is how a new design is synthesised. In the first of the 2007 RAEng seminars, Lipton pointed out that philosophers of science have had little to say on how each new scientific study commences. Thus, Popper seems to see the nearest scientific equivalent to design, the creative process of scientific conjectures, as more an issue of metaphysics than addressable through the philosophy of science [7]. Also, the endeavours of design researchers in investigating design synthesis, seem largely to be so artificial, small scale and usually irrelevant to the practice of complex architectural or engineering design, since these studies try to represent the real world through a student design exercise environment, giving very little insight regarding complex design practice.

However, it is worth considering two studies undertaken in the early days of design research. The first was by Darke, who quizzed architects, rather than engineers, on how they came up with new buildings [19]. It seemed that architects search for a key design feature or generator to provide the basis of getting the new concept. It would seem some ship designers adopt a similar approach by making a style choice (see step 3 in Figure 2 and Table 1). The second study by Daley [20] suggested that individual designers bring a set of schemas to their design creation. Unsurprisingly these were: visual; verbal (echoing earlier comments on communication in engineering design); and value systems. The last echoes comments on societal risk in by Turnbull to the RAEng 2007 series of seminars on engineering philosophy [21]. Given these two pieces of research still sound plausible, then they have some quite profound implications for the all-pervasive application of computers to engineering design.

Something that many advocates of systems engineering [11], and of simple models of the design process, seem to be falsely wedded to is a functionalist philosophy, despite the fact it has long been recognised by architects as just another aesthetic style. Engineering designers should be quite clear: Form does not follow Function. Mies van der Rohe even reversed Sullivan's epigram, hence his pioneering of open plan (for adaptability) high-rise offices [23]. You can't have a dialogue to solve the "wicked problem' of requirement elucidation through a process that describes requirements in "functional" (i.e., non-material) solution abstractions [11]. For such complex products, choosing a potential form requires a choice of style (see Figure 2) to synthesise a design option that then can be tested using appropriate engineering science, human factors techniques and for practical and economic viability.

Two other related issues, arising from the reliance on computers for complex systems design, are those associated with the need to tackle the integration task and with designers' ability to judge the output of complex computer software. Integration requires a sense of the total system, as well as the myriad of details, where the engineering truism that the 'devil is in the detail' applies and most engineers want to get into the detail because they know that is where failure is likely to occur. Given the source of error may lie in the early key style driven overall decision making, one has to be able to see the totality of the solution as part of the integration challenge [10]. Computers can now provide the most wonderfully descriptive output as part of (say) a finite element analysis, but how representative of reality is the modelling? Is it showing the intended behaviour of the system to be constructed, which ought to include the behaviour of the people in the system? How may this develop with the advances in AI and, perhaps more immediately, those of Machine Learning (ML) systems in designing PL&C systems? The author has recently reviewed this issue for the marine design community [23], drawing on insights from Bernstein [24] for an architectural audience, and Perez Fernandez [25] for the marine equivalent. In summary these suggest for many of the more routine tasks in complex design "computers assist in the critical, but more mundane, aspects of practice: those that drive project delivery, technical precision and performative predictability" [24]. This suggests the strategic design decision making (Figure 2 and its more nuanced and human centred realisation suggested by Figure 3 [26]) remains with the human designer, who should focus on the "fuzzy half" of such design practice [15] addressing the trans-disciplinary issues raised by a more holistic vision of sophisticated design practice.

So, what do all these issues mean for engineering design practice, given the ubiquitous presence of electronic computation, not just for number crunching analyses but, thanks to computer graphics, also for CAD, Simulation Based Design and Virtual Reality? This author has a very strong belief, borne not just of practice in designing complex vessels but also involvement in the research and development of computer aided preliminary ship design tools, that the crucial word in CAD is aided. Thus, any recourse to "black box" CAD systems or optimisation routines that leave the human designer as little more than a key board operator, unaware of the basis of the synthesis process and the decision making of his or her, so called, design tool, has to be strenuously resisted. A more recent RAEng workshop [27] led by Peter Brook on behalf of INCOSE, reassessed the systems approach in terms of "Elegant Design" in the light of the current challenges, not least Global warming, and that therefore a more Trans-disciplinary approach was required.

A measure of this more holistic approach to engineering practice can be seen in Figure 3. This takes the strategic decision making for complex vessels of Figure 2, and for a particular environment (that of naval ship acquisition) provides a "rich picture" [28] of the seemingly rational (engineering design) process, showing it to be a very human and social activity with many interventions from outside the conventional diagrams.

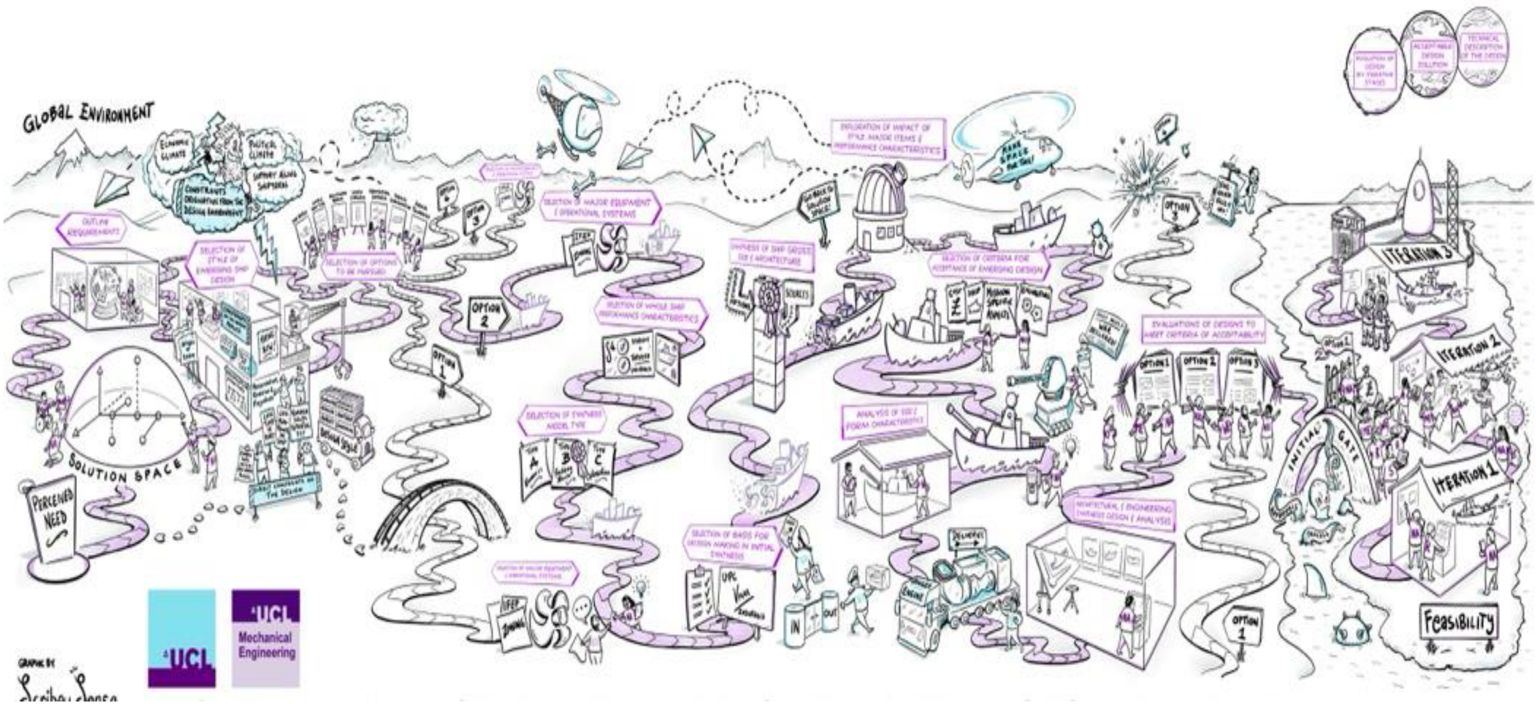

Figure 3. Rich Picture Graphic depicting a Typical Early-Stage Naval Ship Design Process [26]

Four key principles were stated:

1. All systems should be treated holistically;
2. Interventions should result in elegant solutions (i.e., useful, resilient, efficient and with minimal intended consequences);
3. Achieving the goals require understanding and controlling complexity;
4. These principles apply everywhere (i.e., for specific inventions, in responsible enterprises; and engaged responsible disciplines).

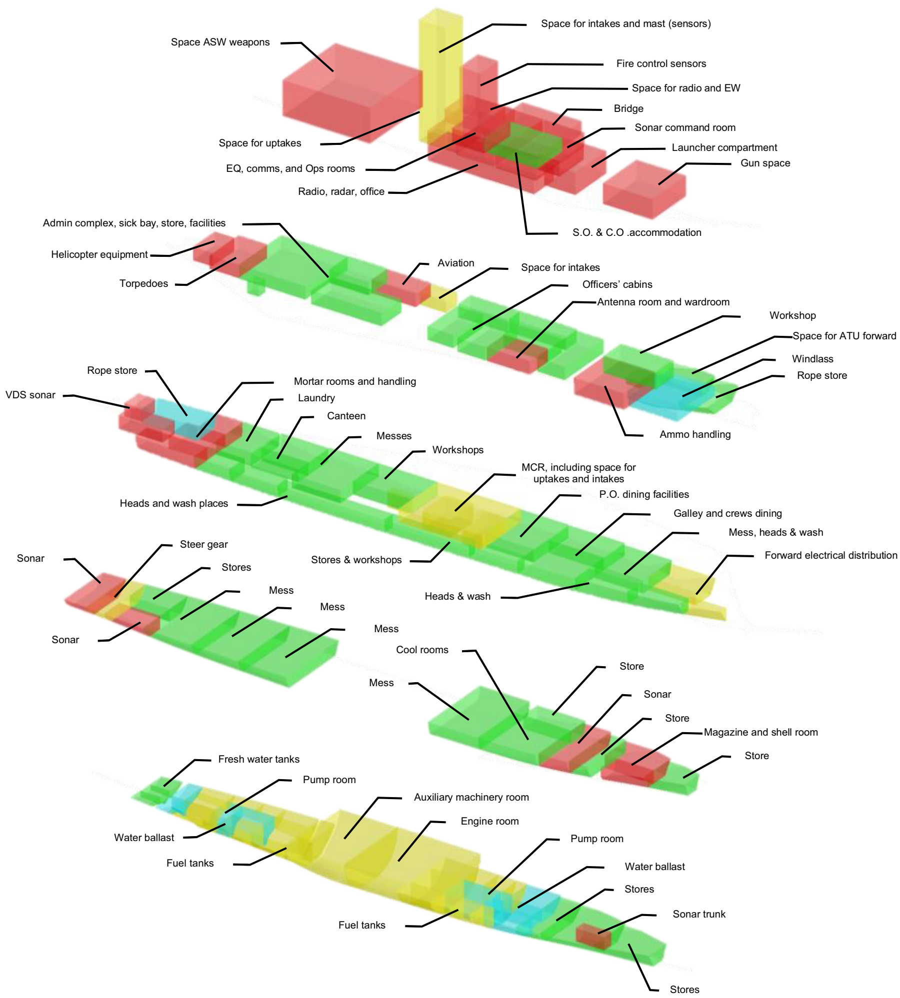

Figure 4. DBB representation of volume granularity of a rapid sketch ship case study [35].

5. Are we still in search of a philosophy of engineering design?

Over the last forty years design methodologists have explored the philosophy of design. In a special issue of Design Studies on the philosophy of design, [28] the editor concluded that the philosophy of design was an immature union of philosophy and design research in “the pursuit of insights about design by philosophical means” [3]. Given philosophical practice is concerned with “the principles underlying any sphere of knowledge” [30], this would all seem to come down to investigating the principles that lie behind the practice of design. The issues of function and form creation were prominent in that special issue, as were the issues of demarcation and taxonomy. However, the link to engineering is debatable by some – a recent book on The Philosophy of Design [31] specifically ruled out engineering design from that author’s philosophical consideration, yet the much more coherent publication by Nelson and Stolterman [32] (comprehensively reviewed alongside [31] in [33]) sees design as being more than creating products and systems (however complex). Rather they see it encompassing the creation of new things, and covering “technologies, organisations, processes, systems, environments, ways of thinking” and thus beyond “architecture and graphic design” and including “organisational, educational, interaction and healthcare design”, proposing a trans-disciplinary perspective, as part of providing a comprehensive “design culture” of enquiry and action [32].

However, the second element in engineering design is the practice of engineering and the RAEng seminars recognised that consideration of a philosophy of engineering – the principles behind our practice – has been overdue. Section 4 has outlined some of the philosophical issues relevant to the future practice of engineering design, which should be convincing evidence that there are some important principles to address. Yet engineering still lacks the status it ought to have and fails to attract and retain the brightest young people in sufficient numbers with one element in that being a certain feeling or belief of intellectual inferiority vis a vis the sciences. Understanding what we are doing and articulating this with intellectual rigour conveying the worth and excitement in our discipline, could counter this misapprehension. Such an endeavour needs to be done without simplifying and straitjacketing the practice. In this regard, the sophistication of the practice of engineering design has been articulated in [10] and that has been recognised [34] within the profession of ship design.

So, what do we want from a philosophy of engineering design? Without being prescriptive and trying to reflect the creativity and sophistication of that practice, this author has pushed, at the front end of complex engineering design, for a more inclusive approach to computer aided design. This has introduced, at the initial design synthesis, a representation of the physical architecture of the artifact, as a set of three-dimensional building blocks (see Section 6 of [10]) to create new designs “inside-out” rather than driven “outside-in” by the hull form in the historic manner of naval architecture [8]. In doing so the impact of the design building blocks on the design is integrated with the existing numerically based synthesis and the application of the relevant engineering sciences to achieve a balanced solution (see Figure 4 from [35]). This is a way of fostering a designer-led approach that is creative and holistic in engineering design terms and better able to respond to modern “elegant design” demands for trans-disciplinarity. The approach recognises the complexity of designing engineering products, as can be discerned from Figures 3 and 4 and spelt out in [10]. In common with all engineering practice, to produce such designs requires domain knowledge and experience; it is thus a challenge but also provides a more philosophically satisfying approach to complex design.

References

[1] D.J. Andrews, Philosophical Issues in the Practice of Engineering Design, In: *Proceedings of RAEng Seminar on Philosophy of Engineering,* London, March 2007. Published London 2010, pp. 35-44.
[2] Royal Academy of Engineering (RAEng), *Philosophy of Engineering*, Volume 1 of the proceedings of a series of seminars held at The Royal Academy of Engineering in 2007, RAEng, London 2010, pp. 1-72.
[3] P. Galle, Philosophy of design: an editorial introduction, *Design Studies,* Vol 23 No 2, 2002, pp. 211-218.
[4] E.S. Ferguson, *Engineering and the Mind's Eye*, M.I.T Press, Camb. Mass, 1992.
[5] S.A. Gregory, (Ed), *The Design Method*, Butterworths, London, 1966.
[6] B. Archer, Design as a Discipline–Whatever Became of Design Methodology? *Design Studies*, Vol. 1 No. 1, 1979, pp.17-20.
[7] P. Lipton, Engineering and Truth, *Royal Academy of Engineering Seminar*, March 2007. Published 2010, pp. 7-13.
[8] K.J. Rawson and E.C. Tupper E, *Basic Ship Theory*, 5th Edition 2001, Butterworth, London, 2001.
[9] R. Pawling, V. Percival and D. Andrews, A Study into the Validity of the Ship Design Spiral in Early Stage Ship Design, *Journal of Ship Production and Design,* Vol. 32, No. 3, 2016, pp. 1-20.
[10] D.J. Andrews, The Sophistication of Early Stage Design for Complex Vessels, *Trans RINA IJME Special Edition*, Oct 2018, pp. 1-53.
[11] D.J. Andrews, Marine Requirements Elucidation and the Nature of Preliminary Ship Design, *IJME* Vol.153 Part A1 2011, pp. A23-A39.
[12] C. Elliott and P. Deasley, (Eds), *Creating systems that work,* RAEng, London, 2007.
[13] R. Coyne, *Designing Information Technology in the Postmodern Age – From Method to Metaphor"* M.I.T. Press, Cambridge, Mass., 1995.
[14] M.W. Maier, Systems Architecting: An Emergent Discipline? *1996 IEEE Aerospace Applications Conference,* 1996, pp. 1-13.
[15] D.J. Andrews, Babies, Bathwater and Balance – the Fuzzy half of Ship Design and Recognising its Importance, *SNAME Maritime Convention 2022,* Houston, TX, Sept 2022, pp.
[16] H.M.L. Rittel, and M.W. Webber, Dilemmas in the General Theory of Planning, *Policy Sciences,* Vol 4, 1973, pp. 272-280.
[17] D.C. Winter, Getting Shipbuilding Right, *US Naval Institute Proceedings*, June 2007, pp. 16-19.
[18] D.J. Andrews, Simulation, and the design building block approach in the design of ships and other complex systems", *Proceedings of the Royal Society, Series A*, Vol. 462, Nov 2006, pp. 3407-3433.
[19] J. Darke, The Primary Generator and the Design Process, *Design Studies*, Vol 1, No 1, 1979, pp. 36-44.
[20] J. Daley, Design Creativity and Understanding Design Objectives, *Design Studies*, Vol 3, 1982, pp.133-137.
[21] J. Turnbull, The Context and Nature of Engineering Design, *Proceedings of RAEng Seminar on Philosophy of Engineering,* March 2007. Published RAEng London 2010, pp.30-34.
[22] D.J. Andrews, The Expanding Scope of Ship Design Practice, *Keynote to IMDC2024*, Amsterdam, NL, June 2024, (forthcoming).
[23] C. Norberg-Schultz, *Intentions in Architecture*, Allen & Unwin, London, 1963.
[24] P. Bernstein, *Machine Learning: Architecture in the Age of Artificial Intelligence*, RIBA, London, 2022.
[25] R. Perez Fernandes, *Artifical Intelligence versus Engineering Intelligence*, 2023 President's Invitation Lecture, RINA London, 1st Nov. 2023.
[26] D.J. Andrews and D.A.W. Andrews, A New Way to Visualise the Design Process of Complex Vessels, *The Naval Architect*, Jan 2021, pp. 16-19.
[27] RAEng On-line Insight Event on *A Model for Transdisciplinary Design*, 23 Nov 2021.
[28] T. Berg and P. Pooley, Rich Pictures: A valuable means to explore complex IS issues, *UK Academy for Information Systems Conference Proceedings 2012*, 2012, pp. 1-12.
[29] Design Studies Special Edition on Philosophy of Design, *Design Studies,* Vol 23 No 3, May 2002.
[30] W. Geddes, W, *Chambers Twentieth Century Dictionary*, W & R Chambers, London 1971.
[31] G. Parsons, *The Philosophy of Design*, Polity Press, Cambridge, 2016.
[32] H.G. Nelson, H.G. and E. Stolterman, *The design way*, 2nd Edition, M.I.T. Press, Cambridge, MA, 2012.
[33] D.J. Andrews, and S-O. Erikstad, State of the Art Report on Design Methodology, *IMDC2018*, Helsinki, June 2018, pp. 3-16.
[34] RINA Annual Report 2022: RINA Council Recommended the October 2018 Special Edition paper by D.J. Andrews be "essential reading for all naval architects and marine engineers", RINA, April 2022.
[35] M.H. Mukti, R.P. Pawling, and D.J. Andrews, Computer Aided Sketching in the Early Stage Design of Complex Vessels, *Ocean Engineering* (accepted for publication 2024).