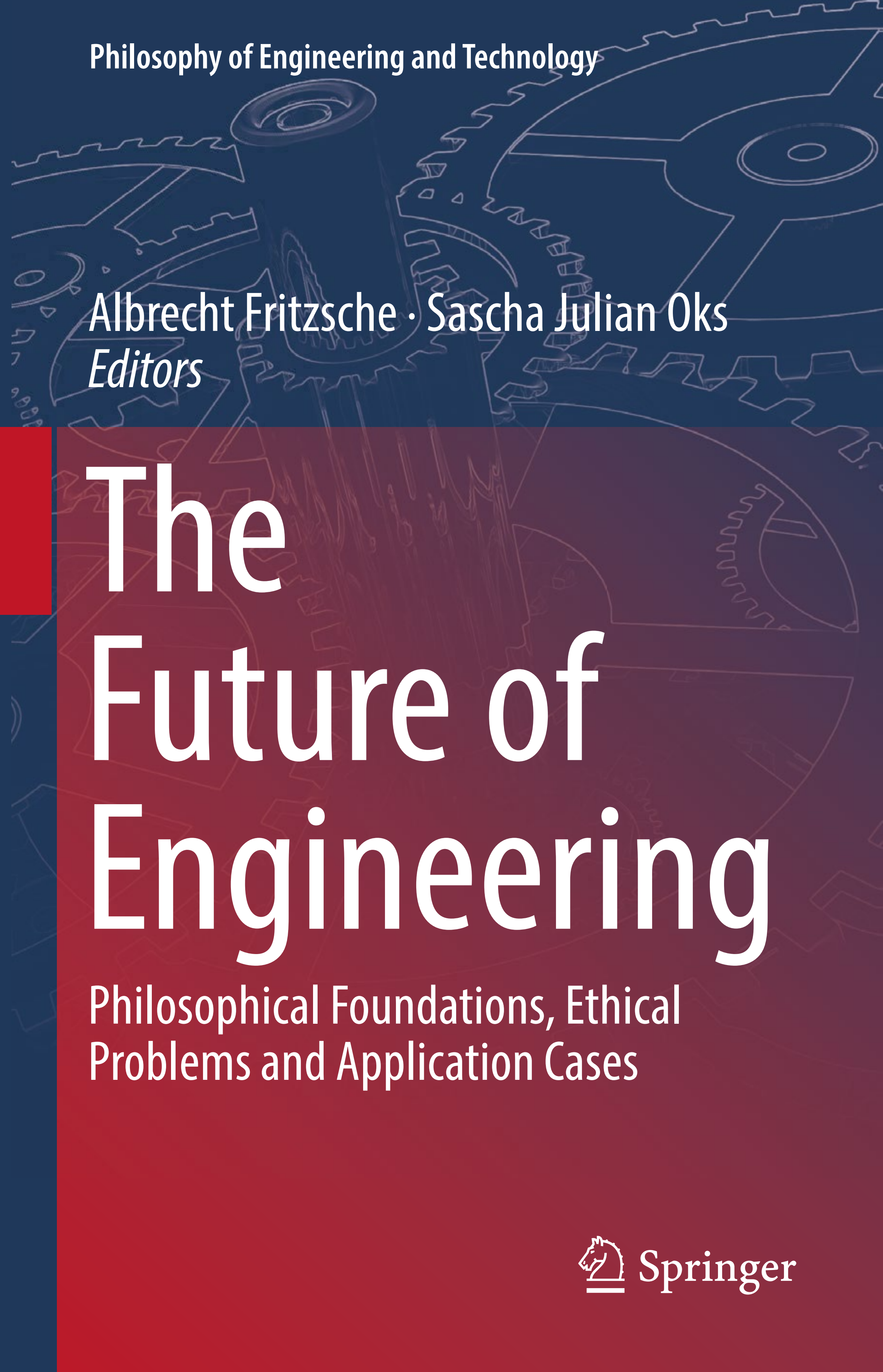

Philosophy of Engineering and Technology

Albrecht Fritzsche · Sascha Julian Oks
Editors

The Future of Engineering

Philosophical Foundations, Ethical Problems and Application Cases

Springer

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Chapter 1
Translations of Technology and the Future of Engineering

Albrecht Fritzsche and Sascha Julian Oks

Abstract Philosophers of technology, engineers, and other experts involved with the same subject matter look at technology in different ways. This paper explores what happens if conflicts and misunderstandings between them cannot be resolved. The exchange between the different expert groups on philosophical questions concerning technology is described as a continuous practice of coping with diversity. This practice can be described as translation, because it connects otherwise unrelated expressions of meaning. It lays the foundation for any further productive treatment of technology in society and future possibilities for the development of engineering. The chapters of this book are used as an illustration of the many different faces and levels of translation in the field.

Keywords Empirical turn · Post-normal engineering · Diversity · Translation

1.1 Bringing Philosophers and Engineers Together

Over the past decades, interest in technology among philosophers has strongly increased, with many understanding that they “need to come into closer contact with the real world of technology, or at least how that world is manifested in technological discourse” (Mitcham 1994, p. 135). Since the late twentieth century, the philosophy of technology has undergone an empirical turn (Kroes and Meijers 2000) and, “with an unprecedented seriousness and determination […] started to engage with the practice of technology and engineering” (Franssen et al. 2016, p. 4). At the same time, engineers have developed increased sensitivity for the larger philosophical and ethical questions which permeate their daily work (Robison 2017). Associations of engineers have published numerous codes of ethics, as well as other documents in which they claim a leading role in decision making processes

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about technical development and take responsibility for its consequences (Harris Jr. et al. 2013). Engineering departments at universities and other research facilities nowadays employ philosophers to teach students and add another layer of reflection to their research activities. In addition, the increasing exchange between engineering, industrial design, management, computer science and other disciplines has lately resulted in various new approaches to philosophical issues in industrial contexts which add further breadth to the discussion (e.g. Halpin and Monnin 2013; Crocker 2012; Guliciuc and Guliciuc 2010).

All this gives philosophers of technology and engineers many opportunities to meet and talk. It often remains unclear, however, what actually happens on such occasions. Do they engage in a common dialogue? Do they just provide source data to one another from which they then continue with their own lines of research? Or is there something else going on? It would be a severe oversimplification to assume that bringing people together to discuss technology leads to a common understanding of the topic and joint activities to solve certain problems. The situation seems to be particularly complicated when philosophers and engineers are involved, since they are both used to making very comprehensive claims about the scope of their research, but from very different points of view. In the philosophy of science, authors like Kuhn (1962) and Feyerabend (1962) talk about incommensurability: a fundamental mismatch of taxonomies, methods, interests and agendas which inhibit the collaboration between different generations or communities of researchers. Philosophers and engineers are likely to be affected by a similar phenomenon in their treatments of technology, no matter how much time they spend with each other. Even if one person is qualified in both fields, he or she may only be able to wear either the hat of the philosopher or the hat of the engineer at one time, but not both, because there is just no way to make them fit. When philosophers and engineers engage in a common dialogue, they may therefore eventually find out that, although they claim to address the same things, the added value they provide to each other's work remains marginal. Instead of starting one discussion which covers philosophical and engineering issues at the same time, philosophers and engineers may in fact merely be able to work side by side, but on their own, unable to make appropriate use of the input they receive from one another.

Most researchers in the field will probably respond that such concerns sound a little dramatic, considering the vast amount of publications which have resulted from joint efforts of philosophers and engineers during the last years. Nevertheless, it seems worthwhile to take a short look at the interplay between philosophers and engineers without assuming that it leads to any kind of integration. On the following pages, our analysis explores this negative view: that the boundary between philosophy and engineering is not crossed, and that occasions which bring experts from both fields together rather create a heterotopic setting, filled with experiences of contrast and ambiguity (Foucault 1971). We do not really consider this as a problem, but rather as an interesting opportunity for a wider treatment of technology, breaking with many lines of thought which have dominated the industrial era. The digital age forces us to look beyond the horizon of mass production, standardized operation and repetitivity and to search for better ways to give account of ongoing change and floating points of reference in technical design and application. Treating the views of philosophers, engineers, and other experts concerned with technology as a true, irreducible manifold can be a first step into this direction and open up new horizons to discuss the future of engineering.

1.2 Translation in the Context of Technology

A conceptual framework for assessing the implications of whether philosophy and engineering are able to integrate together is the notion of translation. Translation has already become a highly popular term in post-colonial studies and surrounding fields of research. We believe that it also offers a lot of potential for a deeper philosophical treatment of technology, because it allows us to avoid inappropriate assumptions of consistence and coherence. In line with the views of translation proposed by Benjamin (1968), Derrida and Venuti (2001), and others, we leave the idea behind that translation is a simple mapping procedure of words and phrases in different languages to reproduce meaning. Translation is more than a search for the right words. It is an attempt to give insight into another way of seeing the world which would otherwise remain inaccessible to the audience. Benjamin (1968) states that translators are concerned with works of art which cannot be reduced to any limited set of descriptive information, as they are inherently connected to the cultural conditions of their production and the personal situation of the author who felt the urge to express him- or herself with it in the particular span of time when it happened. No translation can claim to capture the full meaning of the original. But it can create awareness of its existence and insight into its significance among people who would otherwise not notice it because it is not accessible in their own culture. Through translation, the translator shares his or her own impression of the original by letting the audience go through a similar experience as he or she did in perceiving it, or at least the specific aspects of it which the translator chose to focus on.

This view of translation stands in a long tradition of scholars who favour metaphrasing over paraphrasing. At the same time, however, it takes an important step beyond this tradition as it emphasizes the futility of the attempt to be fully authentic. Translation must be seen as a work of art in its own right. Like the original, it creates an experience which is unique and new to its audience. The original and its translation stand next to each other as artistic expressions in different cultural settings which have a common point of reference, relating what would otherwise remain unrelated and allowing the members of the different cultures to recognize themselves in opposition to the other. Modern approaches to translation following this line of thought therefore like to speak about cultural translation (Roessner and Italiano 2012), setting it apart from conventional translation by recoding a message. Translation can in this sense hardly be discussed in terms of right and wrong, accurate or inaccurate, but rather in terms of connection and separation or appreciation and ignorance of the original and its whole context of creation.

When it comes to technology, a translational approach turns the attention from the usual considerations of design, function and application towards the motivations and choices which go along with the construction and usage of technical devices. It makes us ask why anyone cares to engage with technology, how this happens, and what it means for the relation of this person to others with a similar engagement. Such questions only play a minor role when technology is embedded in an industrial context and separated from aspects of human life which are not related to professional work. Studies of technology which take this context as given help us to understand the behaviour of people who have already agreed to participate and contribute to a common endeavour. We might say that these people have "accepted the rules of the game" or "learned to speak the same language", following some kind of legislative texts or dictionaries which define a common vocabulary. There can be no doubt that this is necessary wherever people are supposed to work together, which we describe as industry. At the same time, however, it obscures our view to all the other people who are for one reason or another not part of the workforce. They appear at best as disturbances and pathologies in the study, because their behaviour is inappropriate in the given context.

Our current view of engineering has emerged alongside the development of organized professional interaction in the course of the industrial revolution. The last years, however, have brought a different side of engineering to our attention which does not fit this history. Michelfelder (2017) describes it as post-normal engineering. It is characterized by the growing importance of value judgments, uncertainty of technical development, continuous negotiations of acceptable risks, participatory design, and open innovation. Post-normal engineering seems to indicate a turning point in industry at which it becomes impossible to ignore what has so far been excluded. Organizational structures of professional work have penetrated human life so deeply that there are no residual spaces left where the disturbances and pathologies could be hidden, forcing us to take a closer look at everything which does not fit to the way how things are designed to be. This is the point where the concept of translation becomes relevant, to explain how variety can continue to exist without integration, how logical conclusions are affected by different values, how a constant need for negotiation can be necessary, and how users can be considered as creative forces in technology alongside designers and builders, even if they may not appear as authors in the same light.

Franssen and Koller (2016) have outlined how the philosophy of language and the study of speech acts in particular can inspire new approaches in the philosophy of technology. The study of translation seems to be a step in the same direction, but with an important difference regarding the range of the statements which are made. We do not presuppose any kind of universality regarding language. Quite in the contrary, we expect that every statement belongs to a given context, and that this context cannot be explicated in its entirety, which confronts us with an unresolvable variety of views. This turns our research interest to the question of how it is possible that the different efforts taken by different people who have something to do with the same technical devices lead to a common achievement when the devices are applied and technology leaves a mark, finds an expression in the world. In other words: we ask how translation in technology can actually proceed.

Technology involves human intention and material structure at the same time. According to Kroes (2010), they are connected through the notion of the function of a technical artefact. During the design of an artefact, engineers make decisions about the material representation of the artefact's function. Kroes (2012) calls this process translation, while noting that the reasoning behind it needs to be better understood. After all that has been said before, it seems that this requires the expansion of the scope of the investigation. So far, research does not seem to have recognized how much translation is involved in every engagement with technology before, during and after the design process. Engineering is not an abstract, combinatorial exercise. Its outcome is a much richer expression of the engineer's view of the world, the perceived need for change in human life, the risks and uncertainties which are involved, the possibilities of development, its benefits, and the control which the designer has over the further usage of the artefact. Considering this, technical devices have to be considered as true works of art, constantly re-interpreted based on different views of the world, which find their expression in the further treatment of the artefact. Borrowing an argument from methodical culturalism (Janich 2006), we would say that engineering is too often studied in the wrong order, starting with the formal process and then adding further aspects about its embeddedness in the world, which leads to claims about intentionality and technical function preceding their materialization in a fixed structure, which might not be helpful in the long run. Again, this might be explained by the fact that technology is often studied in contexts where external influences on the conceptualizations of function have been frozen down in a rigid industrial structure. The digital transformation, however, can be expected to let such structures disappear. Systemic interactions between different agents and ongoing updates of software during the product lifecycle turn manufacturing into a constant, never-ending process, blurring the boundaries of technical artefacts and the distinction of the contributions made by different people. This raises the demand for alternate, more dynamic approaches in the study of technology.

Fritzsche (2017) has suggested the metaphor of a dancefloor to gain a better understanding of translation in technology. Dancing is a cultural practice in which people come together to share an experience, which seems to be the very opposite of an industrial activity which can be broken down to a determinate sequence of jobs which are repetitively performed to produce an output. Every dance is different. It is an ephemeral, momentary work or art which allows dancers to express their experience of the music they hear and the setting in which they have come together. Dancing can be described as a translation on someone else's work of art into one's own (see also Klein 2012). Steps and gestures interpret rhythm, melody and harmonies, and there is no inherent, physically binding criterion which would determine the interpretation. The forms of expression used by musicians and dancers are fundamentally different. In some way, the movement of the dancers is supposed to relate to the music they hear, but how exactly this happens is up to them. And while there are sequences of steps which define a specific dance style over time in a given culture, there is always enough space left for the dancers to make their own, personal choices, and the opportunity to deviate from the rules, ignore certain options, set the emphasis differently, and contribute to the further development of the style. One might think of the music as the design of the dance, which affords a certain dancing behaviour, and the rules of the dance are its organizational structure. When dancing is moved from the dancefloor to the stage, it can be said to be industrialized, reminding us of the parallels in the development of bourgeois culture and industry during the last centuries. Output, coordination, and repeatability become more important than individual expression, the references between music and movement are frozen down to one specific relation, determined by an expert, a choreographer who, like an engineer, takes charge of the entire scenario and makes it work. Back on the dancefloor, everyone takes responsibility, contributes to innovation, and looks for an alignment with the other people who are involved. This describes the kinds of processes which need further attention in the philosophy of technology.

1.3 Foundations of Futures

Pitt and Shew (2017) describe the ongoing research in the philosophy of technology as an exploration of different spaces for the future. The translational perspective turns the attention to spaces which are not given and explored, but emerging from the engagement of different people with a common subject matter. Translation as a creative act creates conditions under which development becomes possible and progress can be made. In the context of Actor-Network-Theory, Callon (1986) has described this as a process of negotiation and delimitation. For us, it is important to emphasize its results are not durable. They have a temporary quality, depicting an agreement which has been reached in the moment and needs to be revised again and again. The process of negotiation and delimitation is constantly re-initiated, turning it into a practice which is less interesting because of its output and more because of the fact that people commit to it. Again, the metaphor of a dance comes to mind, which never stops attracting people, no matter how much they have achieved with it before. This kind of practice is the main focus of our investigation.

Bhabha (2004) has coined the notion of the “third space” in-between cultures to describe where the staging of cultural difference proceeds. This third space is considered as an essential prerequisite for development and insight, as it allows people to act out their conflicts, to set themselves apart from each other and, by this, also to define the common ground between them. Wherever philosophers and engineers come together to discuss technology, they meet in such a space, due to the different training, experience, interests, and problems which affect their treatments of technology. Even if they all leave afterwards more confused than informed, the fact that they take time to address technology together and experience the full range of questions to be asked and answers to be given adds something important to research in both areas. It makes us aware that the phrase technology is a hollow shell if it is not connected to experience and that it requires a continuous effort to make technology fit in human life.

The forum for Philosophy, Engineering and Technology (fPET) provides a perfect opportunity to study a third space. Every second year, fPET assembles philosophers, engineers, and other experts to discuss philosophical aspects of technology design, management, and innovation. The participants are invited to share their experiences and opinions in an open exchange across disciplines and explore the possibilities to create connections between their work and others. The fPET meetings do not only give insight into the latest state of research in various fields; they also show how well the lines of thought pursued by the different experts resonate with each other, where they take steps into the same direction and where they go different ways in their treatment of technology.

The chapters of this book are inspired by the fPET conference hosted in 2016 by Friedrich-Alexander University in Nuremberg, Germany, which assembled researchers from all continents and major industrial regions. In addition to philosophers and engineers, the organizers also invited management scholars, designers, and artists to give account of the increasing importance of other professions to the development of technology. Furthermore, fPET 2016 involved decision makers from industry, who presented practical problems of engineering to explore solutions together with academic scholars. The participants of the meeting therefore had many opportunities to reach out across the various boundaries of their professional domains to exchange with others, discover common interests, and acknowledge differences. We believe that this kind of interaction is highly important for research to keep in touch with the actual practice of engineering and to set the foundations for any further engagement in the subject matter. What we will observe as engineering in the future depends on the way how we relate our current treatments of the subject to each other.

1.4 The Contributions to this Book

In selecting the contributions to this book, we have tried to recapture the atmosphere of fPET 2016, the liveliness of the discourse, the contrasts between the participants, and the surprises resulting from the juxtaposition of their perspectives. The list of authors includes philosophers, engineers, and managers, experts from highly developed countries and others which are still going through a period of rapid change. All authors have impressed us with the quality of their argument and the originality of their perspective, which will hopefully give readers an idea of the many different facets and layers of translation which deserve attention in our field.

In the next chapter, Zachary Pirtle, Jay Odenbaugh, and Zoe Szajnfarber explore the benefits of pluralism on a practical level. Their contribution, called ""The One, the Few or the Many?": Using Independence As a Strategy in Engineering Development and Modeling", deals with problem solving strategies in engineering which take different analytical approaches in account. In particular, they compare the RAND

Corporation's parallel path strategy with Richard Levins and William Wimsatt's approach to model independence for using multiple models to assess the same system. They draw important conclusions about the desirability of independence in solution approaches with respect to the uncertainty of the given problem situation.

Sjoerd Zwart, Maarten Franssen, and Peter Kroes also take a look at engineering practice in their contribution called "Practical Inference—A Formal Analysis", focusing on the question to what extent technical norms can be said to have a truth-value, and under what conditions practical inferences are deductively valid. The authors rely on dynamic logic (PDL), in particular the deontic version of PDL by John Jules Meyer. Bringing the argumentation to a close, Zwart, Franssen, and Kroes address issues of the reliability instead of truth-value, and the defeasibility of practical inferences as they occur in engineering practice.

Mark Thomas Young turns the attention to the role of tacit knowledge in engineering design. In his contribution called "Intuition and Ineffability: Tacit Knowledge and Engineering Design", he outlines the nature and role of intuition by examining the limitations of attempts to formalize the practice of engineering design. Young identifies correspondences between characteristics of intuition in engineering design and phenomenological aspects of Michael Polyani and Harry Collins' notion of tacit knowledge. Third and final, the solution of an "ineffability problem" is proposed by a phenomenological understanding of tacit knowledge.

Terry Bristol picks up on the topic of knowledge with his outline of "The Engineering Knowledge Research Program". This program is part of a larger effort to articulate a philosophy of engineering and an engineering worldview. Bristol explains the conflicting priorities of engineering when it is understood primarily as a field of science on the one hand and the other as an accumulation of methods for design and problem solving. Bristol postulates a paradigm shift from the scientific worldview to the engineering worldview and matches it with other paradigm shifts in traditional disciplines.

Viola Schiaffonati continues with her work on "Philosophy of Engineering and the Quest for a Novel Notion of Experimentation". She investigates different practices of computer engineering and in particular autonomous robotics with a focus on experimentation. Explorative experiments are introduced as a suitable form for the investigation of novel ideas or techniques without the typical constraints of rigorous experimental methodologies. Schiaffonati reviews extant literature to develop a wider framework of experimentation which allows a more appropriate treatment of the epistemological issues involved in this topic.

Knowledge generation also plays an important role in Nico Formanek's chapter on "Demarcating Simulation". His interest is directed at the outstanding characteristics of computer simulations which give them a special status in research and design. Formanek shows how arguments from philosophical studies of mathematics can be applied to computer simulation. His main concern is the extent to which human justificatory capabilities still remain central in this context.

Wang Nan and Li Bocong continue with their chapter called "Three Stages of Technical Artifacts' Life Cycle: Based on a Four Factors Theory". They direct the attention towards the lifespan of technical artefacts. Like living beings, technical artefacts have a lifetime with a beginning and an end, albeit the kind of mortality is radically different. Wang and Li divide the life cycle of technical artefacts in three stages: creation, vitality, and ending. Reinterpreting Aristotle's notion of four causes, the authors draft a theory of four factors affecting technical artefacts in their lifespan.

José Aravena-Reyes also takes a look back at ancient Greek philosophy in his contribution called "*Métis*: Reconfiguring the Philosophy of Engineering". He revisits the basic concepts used by Plato and Aristotle in their treatments of technology and argues that métis has so far received too little attention. He conducts an etymological analysis to gain a better understanding of métis as a cunning and inventive mode of thinking. Connecting the concept of métis to modern works on technology, Aravena-Reyes seeks to open a new perspective on the role of engineering which is also applicable in ethnic contexts in developing countries, such as the Yanomami culture.

The chapter by Tuna Baskoy deals with "Thorstein B. Veblen's Philosophy of Technology and Modern Capitalism". While Veblen is well known for his social and economic studies, his work as a philosopher of technology receives very little attention. Baskoy argues that Veblen has a lot to say about technology which could enlighten the current discourse in social sciences. She reviews Veblen's writings from a contemporary point of view, highlighting in particular the embeddedness of technology in a wider social context and the dynamic relationship between politics, economy, and engineering.

The wider social context of engineering also plays an important role in Rafaela Hillerbrand and Kathrin Goldammer's contribution. Their chapter is called "Energy Technologies and Human Well-being. Using Sustainable Design for the Energy Transition". The authors investigate the relationship between sustainability and individual well-being and show that current ideas about what constitutes sustainability need revision. They develop a value-sensitive design approach for energy systems based on the concept of central human capabilities.

Erik W. Aslaksen looks in the chapter "Technology, Society, and Survival" at the role of engineering as a medium for human interaction. He discusses recent developments in information technology and their potential to influence societal and political processes, both positively and negatively. His particular interest is directed at scenarios where small groups in society controlling the availability of information. Aslaksen explores mechanisms which can prevent such scenarios from becoming reality, threatening democracy, and to continuity of social evolution.

Andy Neely, Sarah Fell, and Albrecht Fritzsche discuss the strategy behind engineering research and teaching at the University of Cambridge. Their chapter has the title "Manufacturing with a big M – The Grand Challenges of Engineering in Digital Societies from the Perspective of the Institute for Manufacturing at Cambridge University". According to the authors, engineering is in danger of losing its autonomy as a discipline due to increasing interdependencies with other professions. In order to ensure that engineers can continue doing the works as before, new content has to be added to engineering curricula, taken from design as well as business and management studies.

Cecilia Moloney, Cecile Badenhorst, and Janna Rosales discuss engineering education from a different perspective in their chapter called “Fostering Subjectivity in Engineering Education: Philosophical Framework and Pedagogical Strategies”. They advocate a paradigm shift in engineering education to foster the subjectivity in these studies such that engineers gain a better understanding of the connections between their own life values and motivations and their career choice and development. They present insights from a pilot offering of a co-curricular course for engineering graduate students and discuss their implications for future engineering education.

With the chapter on “Managing the State of the Art of Engineering: Learning from Medicine”, Édison Renato Silva, Roberto Bartholo, and Domício Proença Jr. take another step beyond the boundaries of engineering as a discipline. They discuss the state of the art in medical science and present possible learning opportunities for the future of engineering. To this end, both disciplines are continuously compared and collated for potential fields of transferability. This is illustrated by an example: the Patient-Intervention-Comparison-Outcome (PICO) protocol.

Glen Miller leads the discourse of this volume towards the thematic focus on ethics in the field of engineering. In his chapter on “What Ethics Owes Engineering”, he argues that ethics and engineering can influence each other in both directions. Engineering is not only affected by ethical considerations; the opposite is also true. Miller gives three examples how engineering affects ethics, regarding the separation of intentions and ends, the time needed to satisfy basic needs, and the understanding of desire and its social implications.

Hidekazu Kanemitsu reports interesting developments from his home country in his chapter on “New Trends in Engineering Ethics – A Japanese Perspective”. Even though the subject of engineering ethics is widespread in the Japanese education system, current curricula “lack the normative sources to evaluate the moral design of problems, and sometimes fails to motivate students to learn engineering or/and engineering ethics by emphasizing on the negative aspects of engineering”. In the further course of the chapter, Kanemitsu discusses aspirational ethics in addition to the preventive ethics as a potential solution.

Nolen Gertz takes us on another kind of journey through different schools of thought on technical design in his text on “Nietzsche, Postphenomenology, and Nihilism-Technology Relations”. Questioning the idea of leisure as liberation, he reviews the positions of Aristotle, Marx, Nietzsche, and Ihde on the relation between human individuals, technology and the world. He identifies various parallels, which are then used as a basis to describe a new set of human-technology relations. These so-called “Nihilism-Technology Relations” give a new access point to study technology in human life which focuses more on responsibility than leisure as liberation.

Bruno Gransche continues with his chapter called “Assisting Ourselves to Death – A Philosophical Reflection on Lifting a Finger with Advanced Assistive Systems”, which is concerned with advanced assistive systems and their role as intermediaries between humans and the world. Drawing on the works of Hannah Arendt, Gransche investigates the changing relationship between humans and their labour they perform and raises strong concerns against the idea of a comprehensive service, which destroys the possibility for further self-development.

Kristen Psaty concludes the book with her contribution on “Engineering Privacy on the Scaffolds: An Existentialist Examination of Privacy by Design”. Psaty looks at the possibilities of engineers to provide privacy in digital environments by design. Based on the works of Jean-Paul Sartre, she argues that engineers need to consider the users of their systems as the others, in a relationship which allows the feeling of shame. This, however, is not easy to achieve in the context of modern information and communication technologies.

1.5 Our Gratitude

We are indebted to a lot of people who helped us make this book possible. This includes everyone involved in the organization of fPET 2016 at the Institute of Philosophy and the Institute of Information Systems of Friedrich-Alexander University Erlangen-Nuremberg, and all our supporters at the Association of German Engineers (VDI), Fraunhofer IIS, acatech, and Technology Market Strategies (TMS). The team at Springer has been very helpful and cooperative in every step of the publication process, and our special thanks go, of course, out to Pieter Vermaas, the general editor of the POET book series for his advice and encouragement. Most of all, however, we would like to thank everyone who attended fPET 2016 and contributed to our common effort, in particular the authors who have written the texts for this book. Keep on dancing!

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Chapter 2
"The One, the Few or the Many?": Using Independence As a Strategy in Engineering Development and Modeling

Zachary Pirtle, Jay Odenbaugh, and Zoe Szajnfarber

> *"No one will deny that a problem cannot be fully formulated until it is well on its way to solution. The real difficulty, the nub of a problem lies somewhere amongst the subproblems…The nature of the problem can only be found by examining it through proposed solutions and it seems likely that its examination through one, and only one, proposal gives a very biased view. It seems probable that at least two radically different solutions need to be attempted in order to get, through comparison of subproblems, a clear picture of the 'real nature' of the problem" (Marples 1961, "The Decisions of Engineering Design. p. 64, source found due to Lenfle 2011).*

Abstract There are choices about the number of ways to approach and understand a problem. Sometimes finding the one right analytical approach is sufficient. Other times, such as with the Manhattan Project, the use of many approaches is desirable. Increasing independence among multiple analytical approaches, i.e. using a pluralistic approach, can be a good strategy to get knowledge to make decisions and understand a system. We considered two frameworks that have attempted to provide advice to engineering and scientific practitioners on when and how to use multiple analytical approaches. The RAND Corporation's parallel path strategy, as described by R.R. Nelson, is a way of using independent engineering efforts to explore what parts of the design space are feasible, as well as what the cost and schedule would be for different designs. Richard Levins and William Wimsatt's focus on model independence provides motivation and insights for using multiple models to assess the same system. While these approaches may appear different, both rely on using

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a group of analytical approaches where the individual members are independent – or different from—one another. Comparing these two approaches provides suggestions about how to utilize independence to address uncertainties in design and model-systems. We argue that the deliberate creation of independence among engineering developments and models should be tied to key uncertainties in the model or system. With relatively low uncertainty, choosing one approach may be acceptable. Both suggest that there can be (but are not always) benefits from using multiple approaches, which can increase accuracy and reduce cost. Using a few independent approaches – as opposed to many – may be more desirable when there are only a few bounded uncertainties about the system.

Keywords Pluralism · Model independence · Parallel paths · Richard Levins · Richard Nelson

2.1 Introduction

There is often a tension in the amount of analysis or engineering development one would like to do in an ideal world versus what is cost effective and practicable.[1] One aspect of this relates to whether to use multiple analytical approaches to assess a problem. Intuitively, we know that exploring multiple analytical or engineering pathways can be useful, as is highlighted by the Manhattan Project's work on parallel paths to enrich uranium using different types of diffusion (thermal and magnetic) (Lenfle 2011). Modelers also want access to new and different ways of assessing a problem, including comparing results across multiple models (Levins 1966; Wimsatt 2007; Lloyd 2015). However, in the name of efficiency, many engineers seek to or are pressured to focus their efforts, eliminating duplication in engineering developments or modeling (Lenfle and Loch 2010; Hounshell 2000). In both areas, a similar claim is made: parallel engineering efforts are criticized for wasting resources on redundant efforts; and modelers are often asked to provide just one model of a given system, to avoid creating redundant models. The struggle between the pursuit of an ideal versus a practical analysis approach occurs throughout engineering and science. To better understand this tension, the topics of multiple engineering paths and models are worth focusing on because analysts have already established frameworks for when multiple analytical approaches are desirable.

Despite their being of very different natures, the question on whether to pursue multiple models or engineering approaches is akin to asking how many different analytical approaches one wants to use. 'Analytical approach' is here being used as a catch-all term to describe single or multiple units of engineering developments or models. Models are commonly seen as analytical (Giere 1999), whereas engineering developments are seen as more physical instantiations of analytical and conceptual designs (Baldwin and Clark 2000). While engineering developments are physical,

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[1] The views expressed here are the authors' and do not necessarily represent the views of NASA or the United States Government.

progress on a development gives analytical insight into what the final design will be and how long and how much it will cost to build. The engineering parallel path literature discussed later will provide a further description on how one can abstract an engineering development as an analysis approach, thus allowing it to be compared on a somewhat apples-to-apples basis with models as analysis approaches.

When is 'one' analytical approach enough, be it in terms of engineering developments or models? If you need more than one analytical approaches, there is an additional choice on whether to pursue a few (2–4) or many (>5) different paths. How should engineers decide on the number of analytical approaches, and how should you choose how those approaches are different from – or independent of – one another? Engineers often have some intuitive sense of when to use independent approaches but there is little formal guidance and research on when and how to do it. We offer some theoretical considerations and a framework that can help in choosing when one is enough, versus the desirability of pursuing a few or many separate efforts. We focus our guidance on sufficiently complex systems and engineering efforts wherein it can be analytically difficult to establish the best path forward. Some relatively simple systems or designs can be assessed without the need to rely on multiple analytical means.

We have developed advice on whether to go multiple by assessing two frameworks coming from separate literature streams, including the RAND Corporation's work on parallel paths for engineering development and Richard Levins/William Wimsatt's advocacy of independence in modeling. Both give advice on dealing with complex systems. In studying the work of RAND, Sylvain Lenfle's prescription for dealing with complex developments is to forgo a McNamara-like 'rational' single development approach, to instead pursue an old 1950s approach, the *parallel path strategy* (Alchian and Kessel 1954; Klein and Meckling 1958; Hitch and McKean 1960; Hounshell 2000; Lenfle and Loch 2010; Lenfle 2011). This approach is similar to Richard Levins' 1960s *strategy of analysis using independent models*, where multiple analysis approaches assess the same phenomenon, with shared conclusions across models being treated as more likely true. Both attempt to offer answers on how many analytical approaches are needed and, for some conditions, conclude that 2–4 developments or models should be used depending on the nature of complexity of the design or system being explored.[2]

We discuss each framework in order to provide a deeper perspective on:

What are the rationales for using multiple analytical approaches, be it in engineering developments or models? How do these means serve as a 'force multiplier,' where the whole is greater than the sum of its parts?

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[2] Levins evaluated models based on the realism, generality, and precision and claimed there was a tradeoff between these three features, as discussed later. This led to pursuing three types of models for his primary analysis case in the 'Strategy', but he did not have a general rule calling for three different models. However, he was concerned with the manageability of models, and the use of 2–4 models may be at the upper end of what's manageable. He recognized there could be other dimensions for evaluating models. For Nelson, different assumptions could yield different results on the desired number of paths. Also, we note that while Levins and others use the term 'robustness' to refer to this process of agreement across multiple lines of evidence, we focus on the term independence because it is less commonly used and is less likely to be misconstrued (Lempert et al. 2006).

To what extent is independence a key factor underlying the motivation for using multiple? How do different types of independence affect the results?

What general guidance is there for deciding whether to implement “One, Few, or Many” analytical approaches in both modeling and engineering systems development?

To anticipate our argument, both frameworks give perspective on having ‘one, few, or many’ based upon their different reasons for having independence. This is a feature of both frameworks that is underdeveloped, and to which we build upon in our interpretation here. Choosing one, few, or many, should depend upon the nature of the uncertainties that a development team is facing. If one uses multiple, then the choice of which approaches to use should be tied to the types of independence used in the problem at hand. If you’re dealing with a relatively simple system, one may be sufficient. Critically, there can also be a situation where various parts of a system are poorly understood, which leads to many approaches being needed. Alternatively, schedule pressure resulting from some type of Manhattan project-like national emergency can lead to a practical rationale to use multiple approaches to explore the design space. We build on the two approaches here by emphasizing that the benefits of going ‘multiple’ only accrue if the approaches are independent from one another in relevant ways. The analysis of what the key uncertainties are and what types of independence are needed should be led by a subject matter expert with a deep knowledge of the material. Cost and the intellectual ability to manage and understand multiple analytical results across different paths needs to be strongly considered as opportunity costs, but the judicious increase of independence among analytical approaches may be a strategy worth implementing more often than is done today. With these concepts in mind, we will now discuss the two central frameworks of parallel path developments and model independence.

2.2 Framework 1: The Parallel Path Strategy for Engineering Development

David Hounshell (2000) provides the best history of the parallel path strategy, which we draw from here.[3] This was a strategy meant to help guide the military in deciding how many different engineering developments to fund to achieve a given

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[3] As has been explored by Lenfle and Loch, the 1950s RAND trandition of espousing parallel paths was in part pushed aside for cultural reasons for much of the last 50 years. Lenfle convincingly argues that this RAND literature stopped being cited in the 1960s due to U.S. Secretary of Defense Robert McNamara’s desire for a more stream-lined management approach (Lenfle and Loch 2010). This McNamara-led approach led to the creation of the ‘rational’ Stage Gate model of innovation, which assumes that innovation proceeds in a step-by-step fashion and that engineering managers should solely pursue development of a single effort at a time in order to keep costs small. While this stage gate linear model has been much discredited by historians and scholars of innovation, no competing theory of innovation has successfully replaced it (Godin 2006; Szajnfarber 2011).

function. The most famous articulation of the strategy was in the work of Nelson (1961, 1959), who was an economist with graduate training in engineering from MIT. He described the problem that motivated the strategy in his 1962 "Uncertainty, Learning, and the Economics of Parallel Research and Development Efforts:"

"Assume that the Air Force is interested in developing an advanced fighter aircraft and that a certain performance must be achieved if the plane is to have a capability significantly greater than planes currently in force. There are several competing designs. All of them have at least some promise, though considering cost, expected performance, and expected development time, some proposals are more promising than others. However, the estimate of the relevant parameters [such as technical performance and development cost and schedule] are known to be subject to considerable error. What should the Air Force do?" (1962, p. 352).

The Air Force may have received multiple proposals for building the airplane: the different designs may each seem plausible, but perhaps the overall dynamics of the final design for some of the proposal will be more complicated than expected. It can be difficult to know in the beginning which design should be chosen. In other words, the problem the strategy tries to alleviate is: "Yet despite the unreliability of estimates, choices must be made. Given the riskiness of R[esearch] and D[evelopment], what is a good way to make choices?" (p. 352).

Nelson frames an answer based on two approaches. He says that one option is to pick the best initial option, despite the lack of maturity in early estimates. This is a prelude of what Lenfle later calls a 'rational' approach, where a manager or engineer tries to pick the right design at the beginning. However, Nelson feels the uncertainty is too great for this to be a reasonable choice. This leads him to explore the parallel paths strategy as an alternative. His suggested strategy is to pursue multiple alternative paths to accomplish a 'certain performance,' which implies accomplishing a shared, desired function. Nelson goes on to discuss how early estimates about a development program will have high uncertainty, with initial cost, schedule and performance estimates being doubtful. The uncertainty about what designs could work is the key motivator here. One can also be uncertain as to whether any of the designs can meet a given functional goal; perhaps a goal is not achievable. Given that "the early stages of development are usually the cheapest stages," and that uncertainty about a development/design's potential decreases as development continues, funding parallel paths can be a way to cut down the overall cost of development for high complexity projects.

Nelson admits limitations to his argument and in generalizing it to all of engineering.[4] Recent studies look favorably on Nelson's analysis (Scherer 2011), with

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[4] The two main caveats are about certainty of the design and the role that schedule pressure plays in motivating his argument. First, the argument is not a certain one, and it is always possible that another approach could be successful. For example, he said "It is true that the atomic-bomb project, the method that actually produced chain-fissionable material for the first bombs was considered relatively unpromising early in the program…But it might well be argued that had all our money and effort been allocated to this latter method, it might have produced material not only just sooner, but sooner than the former method" (p. 362). However, Nelson's argument and calculations suggest that the use of parallel approaches will be right more often than not. Second, Nelson

Lenfle and others deeming the parallel path strategy to likely be useful for complex, schedule focused developments. Based on his caveated assumptions, Nelson predicted that 2–4 projects would be the ideal number of projects for the given complexity of systems. He says the key distinguishing assumptions for his analysis are:

1. “the cost of running a project during the period of competition; [where low prototyping costs make running multiple paths more feasible]
2. the expected improvement in estimates during the period of competition; [with greater insight post-prototyping enabling choice of a lower life cycle cost effort]
3. the difference among the cost and performance estimates of the competing projects, [with greater uncertainty increasing the value of going multiple] and
4. the design similarities and differences of the competing projects.” [where the more similar the projects are, the less value there is in using multiple; this ties to our discussion of independence below] (p. 361, emphasis added).

Nelson argued that the parallel paths approach is best used to fund projects initially before down-selecting based on a few prototype development efforts. There can be diminishing returns when one funds many paths, as more of them are likely to explore the same design and cost uncertainties. While Nelson does not cite this, there are present day examples of bringing multiple efforts to a fully operational state, such as the use of multiple providers for space launch vehicles.

Despite these caveats, Nelson feels his conclusions still show that “we should be wary of damning the wastefulness of independent and competitive efforts” (p. 363). We want to more precisely interpret what types of independence Nelson had in mind here. Nelson says he wants to make sure that there’s enough decentralization and diversity of approaches so that there is a de facto amount of what we will call independence involved amongst the collective paths. Implicitly he seems to view the projects as needing to have different odds of success, which might come from them working based upon different types of physical principles or being managed by different types of organizations. His approach also implies some ability to combine and share insights across approaches: Lenfle 2011 builds on this in his discussion of how the Manhattan Project was able to combine the different uranium enrichment efforts (thermal diffusion, magnetic diffusion, and creation of plutonium) to greater overall benefit, merging and changing the paths to get the best outcome. In this sense, there can be a synergy across the multiple paths that leads to a ‘force multiplier’, wherein the end result is superior collectively than it would have been with just the individual pats.

In sum, Nelson advocated 2–4 different engineering developments be brought to a prototype phase given his assumptions based on very complex engineering developments, which would reduce costs and accelerate time to completion. The parallel path strategy was originally conceived as a way of getting knowledge about different possible designs, how much they’d cost and how long they’d take to accomplish.

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indicated that time concerns may be the biggest reason to embrace a parallel paths approach (p. 361): if one does not care about time, then you can wait for more research to help provide clarity on what development option should be pursued.

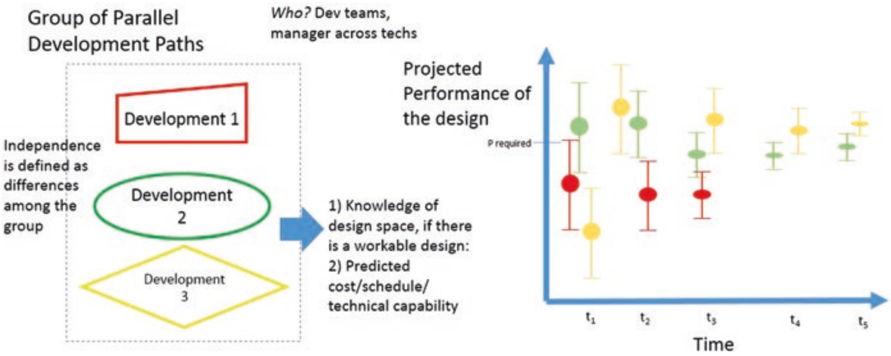

Fig. 2.1 Schematic of the parallel path framework. Downselecting at different times can yield different results based on the characteristics of the project and the remaining uncertainty in a design. Knowledge of the cost and schedule for the development will also grow over time

We deepen the interpretation of the parallel path strategy by emphasizing that the different development paths (later referred to as analytical approaches) must be independent if there is to be a sufficiently rich exploration of the possible design space such that the benefits of a parallel strategy will accrue. The overall schematic shown in Fig. 2.1 describes the strategy. It shows how the expected performance of a given project may change as it evolves over its life cycle, and the best device may be different at the end than what was there at the beginning. The ultimate functional performance as well as its cost and schedule become better known as time goes on.

2.3 Framework 2: Model Independence Among Ensembles in Levins and Wimsatt’s Robustness Work

There has been a growing amount of literature specifically exploring the virtue of using independent models, much of it originating with the work of Richard Levins and William Wimsatt (Lloyd 2015; Weisberg 2006). This ‘strategy’ to use multiple, independent models developed out of a concern to get more accurate knowledge about complex systems. Population biologist Richard Levins presented this in his 1966 article “The Strategy of Model Building in Population Biology.” In contrast to efforts to create a single, comprehensive model of a system, Levins presents three different models that he uses to analyze an ecological system. The ‘Strategy’ he employs is explicitly about trying to create multiple, independent models of an ecological system that have differing levels of realism and vary in their level of generality and precision. Each of Levins’ models are based in evolutionary theory and ecology and can be used to examine similar, specific claims, such as how species evolve in uncertain environments. Levins has caveats about the inherent limits of each model, but notes that each model is designed to use different assumptions to analyze the same system.

His goal is to get conclusions that are supported by multiple, independent models: insights so agreed upon are more likely to be accurate. Levins states his goal as: "[I]f these models, despite their different assumptions, lead to similar results we have what we can call a robust theorem which is relatively free of the details of the model. Hence our truth is the intersection of independent lies." (Levins 1966, p. 423). Again, while there are still ongoing academic debates about the virtue of exploring a system using independent models, the rough consensus of the literature is that there is a positive epistemic benefit from engaging in and pursuing this type of independence. The literature discussing Levins' paper has been growing, with there now being over 1350 citations listed on Google Scholar by both ecologists and scholars studying the epistemology and methodology of modeling (Orzack 2012; Levins 1993; Orzack and Sober 1993, Odenbaugh 2006, Parker 2011). Beginning in the 1970s, Wimsatt (1981) saw robustness as applying to any type of scientific reasoning or activity, not just including model building and analysis.

We here build on Levins work by deepening our interpretation of how different the models should be from one another: they must be meaningfully independent from one another in order for there to be an epistemic confidence gained from their agreeing on certain claims. Pirtle et al. (2018) describes two alternative modeling strategies, one where there is a group multiple, relatively simple models, in contrast to a single, exquisite model. Both could look at the same phenomena and see things at different levels of resolution. Because independent but smaller models have different vantage points, they might be better able to represent and see features of the system under study. In this sense, the combined set of models can be a 'force multiplier,' where the combination of multiple results improves the work of the whole. This general strategy is captured below in Fig. 2.2, which shows how the collective performance of an ensemble of independent models might be stronger than an individual one.

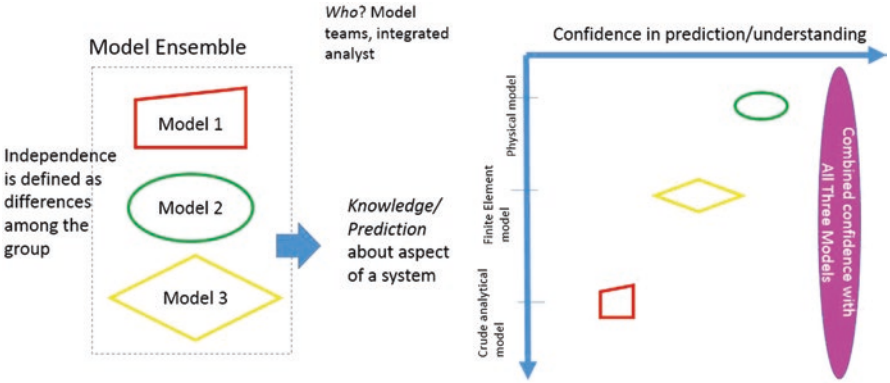

Fig. 2.2 Schematic of the Model Independence Framework. The implication is that the collected confidence of a prediction can be greater if it is derived from multiple, independent sources

2.4 Analysis

Table 2.1 summarizes the key issues within each approach, and prepares for the subsequent analysis contrasting the two strategies. We’ll now describe the rationale for going multiple in both approaches, but it is first important to re-introduce the concept of independence. We highlighted that this is a critical part of both

Table 2.1 Summary of frameworks and their relation to independence

Parallel path (PP) approach	Model independence (MI) approach
Goals: Primary: Increased confidence of choosing a design can achieve a given function. Secondary: knowing the cost, schedule and ultimate capability of a project	*Goal:* Increased confidence in knowing about an empirical system
Key Proponent: 1950s/60s RAND Corporation (inc. Richard Nelson)	*Key Proponent:* 1960s Population Biologist Richard Levins; William Wimsatt 1980s on
Famous Examples: Atlas and Titan rockets, Nuclear Submarines, Manhattan Project, NASA Commercial Crew	*Famous Examples*: Ecology, models of group selection, climate models
Key rationales for going multiple:	*Key rationales for going multiple:*
§ 1) Delays assessment until better information is provided (developments always acquire information as they get farther along the development pathway). Potentially lowers overall cost	§ 1) Multiple views are less likely to miss something – using ‘unrelated chunks of physics’ (Hacking 1981) are likely to see different phenomena
§ 2) If there is (some) independence, some technologies or projects might work better or worse for a variety of reasons	§ 2) higher confidence in shared results
§ 3) if there is cross pollination alongside independent projects, we might learn more about what works and what is possible as a result of communication, thus improving all designs	§ 3) can be less costly, depending on the situation
Common number of paths chosen: When there is a significant uncertainty and schedule and other needs important, finds 2-3 paths to be desirable	*Common number of paths chosen:* Levins used 3 models, with different levels of abstraction. Number of models is limited by the mind’s ability to understand
How independence underlies the rationales	*How independence underlies the rationales*
§ For 1), it is not applicable	§ For 1 and 2) to ‘see differently’ makes you more likely to see new features. Independence helps prevent being fooled by some error or false datapoint
§ For 2), independence can mean that the projects face different road blocks, or need different breakthroughs, some of which may be easier to achieve	§ For 3) Agreement can be a value multiplier (as long as relationship is known and has the right kind of difference, as with interferometry (Hacking 1981))
§ For 3), exploring different parts of the tradespace can enable more learning	