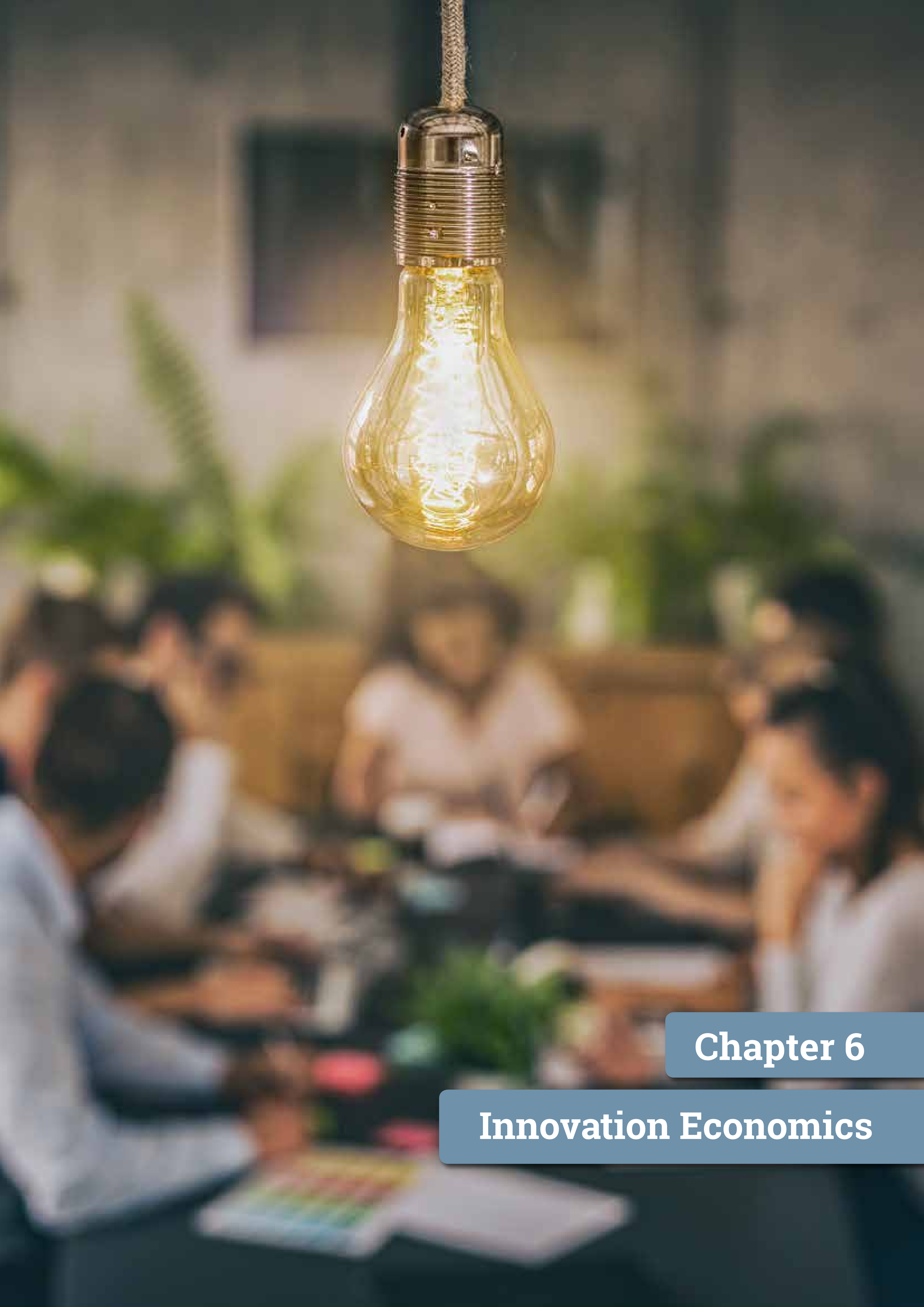

Chapter 6

Innovation Economics

”

Well there happens to be some conditions when you apply for such an innovation project. You need to have different stakeholders from different places. You couldn’t just make an innovation project within your own university.

(Elias, university researcher, robot developer, WIPER)

◀ Innovation and technological development are the result of knowledge-based collaborations within heterogeneous networks of actors.

6. Innovation Economics

You will find here

- Overview of several perspectives on micro-level product research, development, and design
- Overview of the meso-level process of product research and development in innovation networks
- Overview of three long-term, macro-level processes of the industry lifecycle
- Empirical support from REELER cases for complications

You will acquire

- Awareness of how robot developers need to bootstrap out of the dilemma of specification sequentially in developing new robots
- Awareness of how bounded rationality and cognitive limitations have robot developers engage in develop-test-plan cycles
- Awareness of how uncertainty has robot developers engage in 'staggered expansion' of stakeholders included in defining requirements, testing products, etc.

The REELER project is concerned with identifying and creating awareness of ethical issues that may arise in the application of robots, and with providing tools to robot developers for improving the research, development, and design process of robots to increase the ethical acceptability of the impact of the application of robots in practice. Arguably, many aspects of the design are decided upon rather early on in the process of researching, specifying, and materializing a robot, but consequences thereof become clear only later, often in tests, pilots, or even actual implementation. As such, it makes sense to discuss when, why, and how robot developers (should) make particular design decisions, and when, why, and how stakeholders are involved to provide input, co-develop technology, etc.

While the current engineering and product development methodologies prescribe early involvement of end-users, REELER's observation is that in several cases, the robot under development was shelved when it proved to be inadequate for users only after being implemented in practice. Section 6.1 provides an overview of potential causes for design inadequacy from the innovation, behavioral, and complexity economics perspective, notably with regard to the tendencies of individual robot developers to focus on technological aspects and rely on preconceptions of the ultimate application (which may be biased or partial). This is particularly so, arguably, when the development is fraught with technological and market uncertainty, e.g. in case of innovative service robots that need to execute relatively complex actions in socio-technical environments that are hard to predict and require tailored technology. In addition, underrepresented in empirical analyses are robot development projects that do not even make the pilot or implementation phases. Section 6.1 also provides a brief overview of potential causes for these technological failures.

Further complicating analysis of, and thereby providing recommendations on, the process of developing innovative technology is its distributed nature: the research and development are generally not conducted by individual developers, but may also include targeted end-users, and often a group of collaborating developers. Not uncommonly, these researchers and developers are employed by different firms and/or institutes. As such, the interactions of developers and hence (the change in) their understanding of robot technology and directions of technological development are (partially) restricted by the boundaries of the firms and institutes employing them and the nature of their relationships. Development and design activities may also take place at different points in time, hence only partially carrying over knowledge, often embodied in artifacts or codified without the tacit, situated context. Conversely, the robot developers also establish relationships based on their current understanding of the

technology and market, personal preferences and history, language, local culture, etc. Moreover, the robot developers' perception of the design space available to them depends on the components available on the market and capabilities of suppliers. In addition, the market segment and users to target (and thereby the requirements to fulfill) are based on assessment of market and technological opportunities, which are also based on the resources available, capabilities, and commercial viability. As such, there is a complex co-evolution of the perception, technical specification, and materialization of user requirements and the innovation network of economic actors collaborating. As studies revealed that both form sources of technological lock-in and market unviability, innovation economics [1] as well as innovation management both stress the importance of balancing exploration and exploitation of collaborative relationships of economic actors in new product development. In fact, the last couple of decades, innovation management paradigms have evolved considerably, and currently notably emphasize exploration in terms of partners, openness in knowledge sharing, collaboration in knowledge creation, etc.

Indeed, the organization of robot research and development activities has evolved itself as well. In the 1960s, robots were developed mostly completely in-house by a few, mostly competing experimental entrepreneurs seeking to overcome basic technical challenges and targeting applications in rationalized manufacturing processes. By the late 2010s, the robotics industry had evolved to be composed of, on the one hand, established robotics firms supplying mature and modularized robots to manufacturing firms, and, on the other hand, swarms of newly entered entrepreneurs collaboratively researching & developing experimental robotic technologies. Section 6.2 provides an overview of innovation economics insights in the meso-level organization of robot development, notably how particular properties of technological and market knowledge require collaborative governance (in so-called innovation networks), face-to-face engagements, and co-location of development activities. In addition, innovation networks are embedded in innovation systems both facilitating and hampering technology development and market access. In part, when it comes to development of new products, the technological options are restricted and facilitated by the accumulated scientific and engineering know-how, both for the individual developers, the firm or institute at which they work, the (regional) pool of potential partners, as well as for the sector as a whole.

Moreover, the robots that developers seek to provide also change over time; entrepreneurs are developing new robot applications in sectors such as healthcare (e.g. surgical robots, exoskeletons), agriculture (e.g. precision farming, harvesting robots), education (e.g. robotic assistants), etc. REELER also established that there is a considerable role of funding organizations in directing research and developments in individual projects as well as the creation of pan-European knowledge hubs.

Apart from the short- and medium-term determinants of research, development, and design decisions, there are long-term determinants. Over the course of the last decades, the robot development challenges have evolved in a superposition of the traversal of the industry lifecycle (from inception to mature, at least for industrial robots), accumulation of technologies (e.g. refinement of sensors, increase of computing power, emergence of machine learning), growth and diversification of sectors of application (e.g. from the rationalized manufacturing process into agricultural, defense, space, healthcare, and education sectors), new product development methodologies (e.g. from a mostly engineering perspective to recognition of the fuzzy front-end), emergence of strategic management and innovation management paradigms (e.g. from R&D in vertically integrated firms to open innovation), and progressive insights in societal aspects and human factors to be taken into account (e.g. human-robot interaction), etc.

In fact, REELER is bidding robot researchers, developers, and builders to now also properly include a wider circle of stakeholders and to incorporate ethics in design considerations (beyond the usual safety, security, liability, ergonomics, etc.), notably early on in the development process.

Conclusively, this chapter analyzes the process of researching, developing, and building (new) robots subject to (i) the normative new product development methodology used to arrive at products in demand by end-users (regardless of industry lifecycle phase),[2] (ii) the behavioral, complexity, and innovation economic complications in product development such as fundamental uncertainty, bounded rationality, and technological modularization, (iii) the endogenous evolution of innovation networks involved in robotics both facilitating and constraining aforementioned activities, notably recognizing the institutional embeddedness, and (iv) the accumulation of technology within and shifting competitive focus over the course of industry evolution affecting the type of robots targeted and thereby the issues encountered during development.

1 Innovation economics is an emerging field seeking to uncover the economic drivers of innovation, the role of entrepreneurs and institutions therein, the (normatively 'best') organization of and environment for technology research & development, and policies to improve the innovativeness of regions, networks, and firms. Innovation economics studies the organization of development activities from the knowledge-based perspective, primarily concerning the collaboration governance forms, innovation network structure, geographical location of knowledge transfer and creation, etc. Innovation economics and innovation management both argue that certain governance forms, collaborative stances, and organizational structures of these interactions are conducive to the innovativeness and feasibility of technology being developed.

2 References to normativity in this chapter refers to best practices, not the normative 'blinders' discovered through the ethnographic studies.

6.1 New product development process

The past decades are littered with experimental robots that, once piloted in a real-world context, proved to be technologically inadequate, excluded particular users unintentionally, left users concerned about safety or privacy, etc. REELER's research contends that, at least in several of those cases, robot developers may have ignored the actual end-user too much or relied on intermediary spokespersons too much. Here, this contention is followed up with the analysis of robot developers' activities and decisions over the course of a (stylized) new product development process. Notably, while there are well-crafted methodologies to assist developers, these do not alleviate developers of having to cope with intricacies in complex technology development. This includes having to (i) decompose and distribute tasks (with various, possibly unintended consequences), (ii) fix either (hypothetical) user requirements or technical specifications at some point in time (under uncertainty about consequences thereof), (iii) iterate through development process stages upon encountering issues, and (iv) decide when to use accumulated technology, rely on standard methods and tools, etc. and when to develop something afresh. Given the pivotal role of market and technological uncertainty, the necessity to take design decisions regardless of that uncertainty, as well as the need to cope with limitations of understanding in doing so, several REELER researchers have conducted a fundamental experimental study of how human subjects actually cope with market and technological uncertainty as well as technological complexity in product development. Given constraints on the number of pages for this chapter, this section only highlights the main findings and insights on the robot development process.

6.1.1 An engineering and complexity economic perspective

In engineering (including software development and robotics), products are generally developed following design methodologies such as the waterfall model, Cooper's stage-gate model (Cooper 2007) and the NPD framework (Ulrich & Eppinger 2016). These 'product development processes' provide guidelines for activities, generally separated into discrete, consecutive stages (e.g. Cooper 1983), such as generating abstract ideas on the product to develop, preliminary assessment of market demand, formulating (preliminary) user requirements, conceptualization and specification of a functional design, constructing an artifact, conducting tests/ pilots/ trials, and then the product launch and implementation.

Contemporary updates of these development methods , such as 'agile' or SCRUM methodologies, acknowledge both the importance of involving users in various stages as well as pinpoint circumstances in which new iterations are required to reset user requirements, technical specifications, or system design. Moreover, we argue that the development process features, first, decomposition of the robotic system to be developed and subsequent recursive and piecemeal resolution of technical issues, second, multiple iterations over the various stages to act upon feedback, and, third, accumulation of technology that gradually locks in robot conceptualization and components used.

First, whenever, at the start of a development process, a robot is expected to become complex and require not only construction, but also development, and possible even research activities, robot developers may seek to distribute tasks over domain experts and over time. Such a distribution of tasks is, ideally, supplemented with a decomposition of the robotic system into modules and careful orchestration of technological choices across the various modules and across research, development, and design activities. In turn, the development of these modules is broken down into tasks of developing yet lower-level components, etc. Indeed, complex technology development is often piecemeal, recursive, and iterative. For example, think of how computer programs are gradually extended and in which frequent compilation and testing not only establishes a correct implementation but also helps the programmer to decide what to do next and how. Micro develop-test-plan cycles help developers to reduce the cognitive load. However, they also increase the need for relational responsibility (*see 4.0 Ethics Beyond Safety*). Note that robot developers already do partition activities into development of functionalities such as kinematics, motion, sensing, decision making, learning, etc. Moreover, both fundamental and applied research is conducted for most of these (Siciliano & Khatib 2016).

Second, the technological decomposition and distribution of tasks are subject to a specification of the functionality and requirements of a robot. Certain issues encountered at later stages, notably testing and actual implementation, force developers to return to earlier stages of the process and use end-consumer feedback in improving and updating the design. Arguably, at some point in time, robot developers and designers may start to involve end-users or representatives in the development-test-plan cycles (see also the notion of 'staggered expansion' introduced in section 6.2.2). Indeed, REELER's research revealed that the development of robots is definitely not a linear process from development in a laboratory to application. For instance, testing and pilot studies with early robot designs revealed that customers use the robot in unforeseen ways or in an alternative application environment. Indeed, not uncommonly, technological solutions proved to be subpar (i.e. below average) and forced robot developers to revise the user requirements, alter the design, etc., (*see examples in 4.0 Ethics Beyond Safety* and *5.0 Inclusive Design)* on how for instance robot developers need to adjust controllers so they fit smaller hand sizes. So, development failures and process inefficiencies may well stem from the fact that robot developers often develop and design robots with a biased preconception of the end-user in mind or, alternatively, have an intermediary representing the end-user, which introduces his/her bias (*see 5.0 Inclusive Design*).

That said, there are obvious arguments in favor of not involving users intensively at every stage. After all, this would be costly and the organization of pilots would be impractical. Moreover, while waiting for user feedback, robot developers

cannot fix design specifications (often across the interface of robot modules), which effectively delays development activities and thus increases the time-to-market. In addition, more problematically, it is not always clear who is the ultimate end-user to be targeted, as this, in part, also depends on technological possibilities, and the fact that users may not have a concrete idea of how to use the robot in its underdeveloped form (see the **dilemma of specification sequentiality** discussed below).

Matters become even more complicated whenever robots operate in a human-centered service setting (e.g. a hospital, construction site) or become part of a larger socio-technical system (e.g. a farm, or a warehouse) in which the robotics community at large has little (reported) experience. In this case, it may be that the robot may be operated by non-professional users, the human decisions may interfere with the robot's heuristic, there may be changing input from external sensors and options for actuation, etc. (*see 4.0 Ethics Beyond Safety* for examples of how humans and robotic systems are sometimes incompatible). Such 'interactions' may well be so idiosyncratic that they are only uncovered in test trials, pilots, or even actual use after implementation.

Third, over various projects, developers, robotics firms & institutes, and the sector as a whole have accumulated physical artifacts, components, technological solutions, analytical tools, and even problem-solving routines. Moreover, particular dominant designs for the robotic system, communication protocols, and (de facto) standards (e.g. voltage, socket & plug types) have emerged. Arguably, a substantial part of the technology for robots (arm joints, actuators, sensors) is rather mature and is (preferably) acquired 'off the shelf' in new projects, particularly for industrial robots. Developers may (have to) alter or extend these standard components, solutions, and routines when encountering issues in implementation, facing new challenges, etc. So, in crafting new robots, developers may possibly go through multiple iterations of the product development process. It may be necessary to thereby recurse into (re)designing lower-level components, notably the components that prove to be problematic or hold back performance.

In the REELER cases, none of the entrepreneurial entrants into the emerging sectors (e.g. education, construction, agriculture, autonomous vehicles) engaged in radical innovation that challenged the entire robotics architecture. They rather sought to pick mature, standard modules when available. This allowed them to immediately focus on (i) modules that formed either the bottleneck in system performance (e.g. subpar image recognition and poor dexterity in case of a harvesting robot) or (ii) the pivotal technology in the unique, innovative service that the entrepreneur seeks to provide (e.g. personalized learning programs in an educational robot or detecting muscle contraction for actuation in a rehabilitation robot).

Obviously, the use case and application environment of 'downstream' customers (or end-users) reveal both regularities as well as idiosyncrasies that need to be addressed in the robot design. Particularly when physical aspects of components or embedded software have to be altered, the manufacturers 'upstream' have to be involved. As such, over the course of robot research, development, design, and implementation, there may well be interaction of the robot developers with downstream customers/ end-consumers and upstream suppliers of 'standardized' components. The involvement of the 'supply chain' parties in innovation is discussed in more detail in section 3.3.

6.1.2 A behavioral and innovation economic perspective

Particularly the last decade, entrepreneurs have started to develop robots for service sectors (e.g. cleaning, education, healthcare). In these sectors, robots may be operated by various and potentially multiple non-professional users, and notably in less controlled and variable environments. Moreover, robot technology targeted in these sectors typically is more complex than in the traditional manufacturing setting; robots may need to be able to execute many and less routinized activities, may need a high-level of dexterity to handle various objects, may need to process substantial amounts of sensory input data, etc. Moreover, the actual user requirements are not well articulated, the environmental conditions in which to operate are not completely known, the socio-technical environment is changing, some of the technology is still in an early state and evolving, etc. Developers thus, firstly, need to address the 'fuzzy front-end' (e.g., Reid & De Brentani 2004), and, secondly, need to cope with unforeseen opportunities, obstacles, and challenges.

First, for these new (types of) robots, development is not an engineering exercise of translating specific user requirements into a framework of readily compatible mature components picked off the shelf. Instead, robot development gets the character of both (co-evolutionary) market and technological research plagued by path dependencies due to the sequence of specifications as well as inherent uncertainty.

Particularly complicating matters is that (potential) users may have difficulties articulating what they want and how they would use a robot, notably because the robot is yet ill-specified. Moreover, robot developers may have difficulties specifying realistic and sufficiently concrete technical capabilities of a robot without

Dilemma of specification sequentiality (and bootstrapping out): *Fundamental dilemma in new product development that requires a developer to either fix technological specifications to determine detailed user requirements or assume user requirements to determine basic specifications for technology to develop. Both decisions limit future options. The solution proposed here is to 'bootstrap' out by alternating between obtaining user feedback with increasingly more specific designs and trying to materialize new product technology based on increasingly more concrete user requirements.*

knowing how and where the robot is to be used. As outlined above, a typical engineering approach is to *assume* particular user requirements and characteristics of the environment of application, develop the robot to an experimental product, and then engage in adaptation and finetuning after running pilots with the robot in (staged) real-world setting. However, in REELER case studies, such *'forced early neglect'* of users has led to mothballing robots several times (*see Nickelsen, 2018 and Story from the field: Multidimensional inclusion challenges in 5.0 Inclusive Design*). Conversely, selecting particular people as potential users, and taking these potential users' initial ideas for research and development is also risky. After all, technological research activities may stray away from existing technological expertise so leading to (unnecessarily) costly developments (so, focused on 'wrong' targets), may cause squandering resources on research for various market segments ultimately not targeted (so, not focused enough), or ending up with feasible technology but for an ultimately commercially unattractive niche (so, too focused). So, robot developers face - what we coin as - the *'dilemma of specification sequentiality'* and have to choose between two undesired situations. Arguably, a viable way out of this predicament is to gradually 'bootstrap' by alternating between obtaining user feedback with increasingly more specific designs and trying to materialize new product technology based on increasingly more concrete user requirements. So, as such, one would expect a temporal interleaving of market and technology research with a gradual convergence toward a product materialization and specific market segment to target. Note that the various new product development frameworks do stress this iterative character of the process. What is added here, though, is that robot developers may possibly consider running multiple exploratory research projects, thereby postponing irreversible investments that are costly or have an otherwise significant impact on options later. A more detailed treatise is considered out of scope, however a possibility is also to include alignment experts (*see 13.0 Conclusion*).

Uncertainty: *Property of technology and market research as well as product development & design activities that economic actors need to cope with.*

Further complicating matters is the acknowledgment, that research, and development of new technological knowledge is complex, fraught with uncertainty, and does not allow rational optimization. Economic actors not only have to cope with an ill-defined technological target, but also with a partial view of the technologies available, a possibly incorrect understanding of operational principles, partial knowledge of effects of certain changes, etc. In fact, whenever the developers make decisions based on such imperfect information, the consequences of research, development, and design decisions may become clear only later. This also reveals the existence of uncertainties in actors' decisions and reveals deficiencies in the competences of the involved actors. So, the research for and development of new technology is characterized by uncertainties in the viability of market decisions (e.g. *who* are my customers? Are they the same as end-users? *What* do customers want? *How many* customers want this?) as well as uncertainties in technological feasibility (e.g. Can I make X? Does X work for Y? If I change X, would Y still work?). Notably in case of a *breakthrough innovation*, which requires a combination of technological knowledge from, generally, disparate fields, there is -by definition- no a priori quantifiable assessment of whether particular search directions lead to feasible technology or not. In this case, developers need to cope with *fundamental (Knightian) uncertainty* (Knight 1921) (nota bene: unknown unknowns). In developing new technology, developers have to look for a fruitful mix of a wide variety of concepts and technologies from a range of (possibly) related fields. The number of combinations generally is tremendous, and it is practically not possible to investigate all of them. This is further exacerbated by the fact that, for a basic assessment of technological feasibility, an elementary understanding is needed, possibly requiring some basic knowledge transfer, absorption, and imaginary application. As such, developers must overcome *combinatorial complexity*, e.g. by following conjectures on operational principles, design analogies, etc.

Bounded rationality: *Human cognitive limitation in rationalization of decisions.*

A more general notion, found in behavioral economics, is that humans are boundedly rational (Simon 1982), generally lack perfect foresight, and suffer cognitive limitations (e.g. manage to keep at most 7 +/- 2 chunks in memory (Miller 1956)), due to which humans use rules-of-thumb and effort-reduction mechanisms in their decisions (Tversky & Kahneman 1974, Shah & Oppenheimer 2008). In case of technology search, the uncertainty and complexity forces humans researching, developing, and designing new products to rely on (generally) non-optimal, heuristic search strategies. Humans may do so, for instance, by postulating and testing novel operational principles and using them to construct new technological paradigms, develop a range of new product design, trying a near-exhaustive range of new materials (such a 'dragnet' approach was followed by Thomas Edison quite frequently), etc. Clearly, such an approach is experimental, and, as a consequence, pilot studies and tests with targeted users in real-world settings are likely to show that the technology being developed does not meet all user requirements or violates some environmental constraints.

Interestingly, although behavioral and innovation economic researchers have pinpointed such human shortcomings in technology search, there has yet been done little experimental research in actual, operational behavior. REELER researchers with a base in economic disciplines have conducted several behavioral experiments to gain insight into this presented below.

STORY FROM THE FIELD:

Product Design Game – experiment on coping with uncertainty and complexity

REELER conducted an experimental economics study to analyze how humans cope with technological and market uncertainty as well as technological complexity in trying to construct market viable and technologically feasible products given a certain resource scarcity. To this end, a web-based 'product design game' was developed in which subjects have to, individually, try to solve a series of product design challenges. The goal was to build a *working* product constructed by connecting various modules and thereby ultimately providing modules that are *in demand* by as many end-consumers as possible. However, the subject has only a limited number of coins and has to decide *when* to spend these resources and whether to spend these on (a) obtaining information on what modules a randomly drawn consumer wants, or (b) obtaining a (randomly/ selectively) drawing a module from an invisible set. Complicating matters for subjects is that there are only a few combinations of modules feasible and there are only marginal visual cues on whether a combination is feasible or not. Moreover, subjects can (but need not) select a module it owns and focus technological research on finding a module which makes a suitable combination. That said, even if modules form a feasible combination (the product is technically feasible), there need not be demand for it (the product may not be market viable). This 'product design game' thus has human subjects cope with technological uncertainty (e.g. 'I do need this input module, but does it exist?'), technological complexity (e.g. 'can I construct a feasible combination out of this set of modules?'), market uncertainty (e.g. 'what do consumers want?', 'is there demand for the product I have constructed?'), and scarcity.

Distributed over four sessions (three in 2018 and one in 2019), a total of nearly 200 subjects took on a series of 'product design challenges'. After arriving at the university and taking a seat in the lecture hall, subjects received initial instructions on the purpose of the game and elements of the graphical user interface. Subjects were then asked to individually try to complete 16 product design challenges, presented to them in random order. For each challenge ('round'), all mouse moves, actions, obtained market information, discovered modules, created products, feasibility and market viability was recorded and statistically analyzed. Of particular interest now was whether human subjects become better over the course of multiple challenges (i.e. do they gain proficiency in designing?) and what research patterns for design challenges emerges for successful that become successful (i.e. is there a universally superior design roadmap/ new product development process?).

The results for the first six challenges were regarded as the ramp up phase in which subjects have to get to know the graphical user interface, have to get an understanding of what the challenge entails, while the last ten challenges were considered to represent the actual learning of the design strategy. While the experiments showed that subjects indeed start to apply increasingly stable strategies, these strategies differ from the conjectured New Product Development roadmap and, moreover, there were substantial differences between cohorts of subjects. Although plagued by uncertainty, a small percentage of subjects developed a (stationary) heuristic roadmap for product research and development activities which almost always led to a market viable and technically feasible product. Given the resource scarcity, it was not only an effective heuristic, but also allowed the subjects to cope with the combinatorial complexity in conjunction. That said, most subjects fell back to boundedly rational, fast-and-frugal heuristics with relatively poor performance. Apart from displaying visual layout techniques to reduce cognitive load, subjects also had tendencies to overlook market research and overly focus on technological research, sometimes even having a blind spot for particular technological research options. An illustration of the application of boundedly rational strategies is found in Figure 6.1. It contains a photograph of the screen of one of the subjects after almost 75 minutes, so of one of the last challenges.

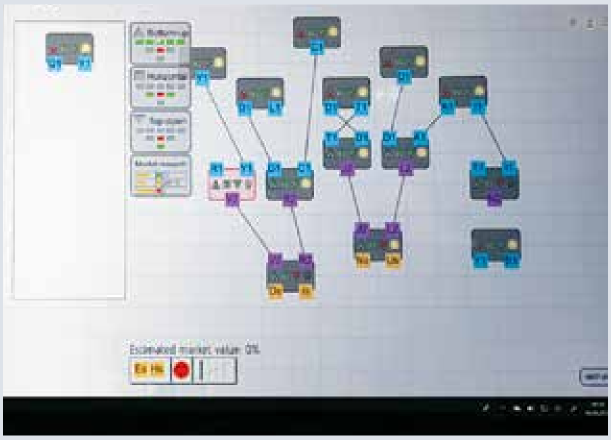

Figure 6.1. Photograph of a screen of one of the subjects, actually of one of the last challenges. (Photo by Ben Vermeulen)

A closer look at the screen reveals that the subject has already constructed a completely feasible product (on the right half of the screen) and has almost finished a second product, which is also almost feasible. In fact, the mouse pointer is hovering over a particular technological

research button (for bottom-up focused search). This choice is indeed part of the most successful strategy, so the subject understands the 'engineering' part of the challenge very well. However, the subject is trying to find an input for the selected module (in light red) and is thus trying to construct a feasible product. However, the market information in the table at the bottom of the screen does not show any demand for the features of that product. As such, the market information is effectively ignored.

On another occasions, another subject was seen to conduct focused technological research (so, again, this rather involved concept was well understood) and managed to construct a completely feasible product. Only then the subject pressed the market research button *for the first time* and sighed and raised its hands into the air in disappointment that there was no market demand for the product! After the session, the subject was asked why (s) he did not conduct market research first before investing so much in technological research. After a short pause, the subject noddingly acknowledged the mistake.

Stressing that the usual caveats apply, the findings from the experiment indeed indicate that humans suffer from cognitive limitations and bounded rationality. There was however a substantial and persistent difference in performance.[3] Translating the findings to the context of real-world product development, developers may be overly focused on developing a top-notch product for the mainstream market segment, thus disregarding indications that this may be technically unattainable. That said, more likely may be that developers are overly focused on developing a feasible product (taking it on as a personal challenge), thereby missing indications that market demand may be absent or insufficient to recoup development costs. In any case, not surprisingly, haphazard or simplistic heuristics in development are likely to be inefficient and prone to failure, which actually underlines that research and development activities require a contextual rationale (e.g. user requirements or technical reasons) (*see 7.0 Learning in Practice*). That said, technological research and development may be too unfocused, effectively overburdening developers. More focused and depth-first developments may increase chances of finding both market viable and technically feasible products (and again these could include alignment experts, (*see 12.0 Human Proximity and 13.0 Conclusion*). There are several more concrete product development recommendations, but these are arguably outside the scope of this publication chapter.

6.1.3 Ethnographic findings and methodological ramifications

The main deliverable of the REELER project is a Roadmap to guide collaborative learning and relational responsibility between robot researchers, developers, and users (and other stakeholders). To this end, extensive ethnographic studies have been conducted to uncover robot designers' assumptions and practices in discovery and incorporation of actual needs of stakeholders in relevant situations. As such, these ethnographic studies could reveal 'best practices', but also biases, shortcomings, and pitfalls. The research findings are reported and used throughout this publication. Benchmarking could then possibly reveal how to ameliorate product development and design practices, notably suggest how to time and tune collaborative learning between robot developers and (different ranges of) stakeholders (e.g. by introducing means to signal and anticipate an emerging lack of human-robot proximity, mitigate or deal with ethical issues).

In the many interviews conducted, there were questions included on the new product development and design process. However, the answers were not giving coherent insights into design processes and provided limited insights on the actual timing for design decisions, what was the status quo of market information at the time, what ultimately led to the design decision made, etc. Indications of these can be found in some of the more comprehensive field studies (e.g. Nickelsen 2018, Sorenson 2018, Hansen 2018). However, in general, not even detailed field studies can cover all the non-linear decisions in design processes. For instance, people have difficulty recollecting actual sources of information and orderly reporting complex interactions. Moreover, they tend to introduce biases in their recollections by selective abstraction, overgeneralization, magnification, etc.

That said, the interviews provided valuable support for claims made in the previous sections. Moreover, analysis across the heterogeneous cases revealed three additional complications in the (organization of the) development process.

First, development decisions are often taken in a distributed and decentralized fashion, e.g. in part in previous research projects, in part embodied in artifacts passed down, sometimes stored in shelved knowledge codified by actors not or no longer involved and hence devoid of (tacit) context. As such, interviewees indeed were only able to reveal parts (in terms of time, innovation activities, social network, and technology) of the design process, and a subjective interpretation at that. Consequently, the actual design space for individual

3 Triangulation with a questionnaire applied prior to the experiment revealed that this difference may be attributable to the computer game savviness of subjects, in part. While results may thus be biased due to instrumentation, it does in fact imply that real-world product developers with a particular aptitude for analytical instruments, problem solving techniques, and the tools used in design, may well be more successful.

developers was often limited, due to which decisions occasionally were suboptimal from a system perspective. In addition, the actual research, development, and design process in practice has been found to be messy, highly iterative and recursive (at least at the engineering level), and at times highly interactive (and occasionally with a prominent role for informal contacts or unusual sources), further complicating attempts to coordinate design decisions.

Second, robot developers frequently encountered complications in fixing user requirements that go beyond mere market uncertainty (or specification sequentiality). The ethnographic material revealed cases in which robot developers faced *trade-offs* (Consumer X does like A and B, but the design can technically not offer both at the same time), *conflicts* (Consumer X likes A, Consumer Y dislikes A), and *in-/exclusion* decisions (Consumer X likes A, Consumer Y likes B, but the design cannot offer both at the same time), occasionally even only during trials or after implementation. Expounding design solutions in an explicit social context helps designers to uncover the existence of such trade-offs, conflicts, and exclusions. Subsequent design decisions are then, ideally, made with an explicit contextual rationale, and particularly those that are time- or resource-consuming or costly to reverse.

Third, as argued before, robot developers necessarily have (more or less) specific user requirements and application environments in mind when researching, developing, and designing their robot. This may lead to complications when the robot is later implemented in a different context not considered earlier. This may concern, for instance, different types of users (e.g. gender, age, handedness), different operational context (e.g. outside instead of indoors), etc. Moreover, as design is always situated, robots inevitably embody cultural elements. This may lead to complications not uncommonly due to rather elementary issues such as the use of particular symbols (e.g. on buttons), language (e.g. speech recognition), appearance (e.g. toy-like), manner of addressing users (e.g. too (in)formal), etc. An illustration is provided in the Story from the field about the South-Korean robot Silbot, found below. While "designing for transferability" may be considered a far-fetched recommendation, some complications may be anticipated by up-scoping the usage considered (albeit risking a lack of focus) (*see also 5.0 Inclusive Design*).

Technology transfer: *The process of adapting technology to particular usage or in an environment different from when originally conceived.*

The Silbot story demonstrates how diverse cultural values challenge processes of technology transfer (Photo by Lasse Blond; See Story from the Field, page 119)

STORY FROM THE FIELD:
The Case of Silbot

In the fall of 2011 and the winter of 2012 experiments took place in elderly care centers in Denmark and Finland where a South Korean robot named *Silbot* was tested. Silbot is developed by a tele-education robot by the name of *EngKey*, invented by the *Korean Institute of Technology* (KIST). The original intention with the robot was to assist English teaching in elementary schools in South Korea where the robot was built to function as a *wizard-of-OZ* English teacher. Wizard-of-OZ refers, here, to the technique by which a robot is operated by a remote teacher outside of the classroom. This function of the robot was tested at 29 schools in the republic between 2010 and 2011 (Guevarra 2015).

Later, Silbot was reprogrammed to facilitate 'brain training' exercises for elderly citizens suffering age-related illnesses such as dementia in a project named *Brain Fitness Class with Elder Care Robots.* The robot was at first tested at the Gangnam-gu Center for Dementia in Seoul and then went overseas to be tested in Denmark and Finland with a mixed and explicitly cultural reception. In Finland, the robot was soon discarded, whereas in Denmark the staff at a local rehabilitation center worked at lenght to make it culturally accessible (Blond 2019). Silbot (and an accompanying robot named Mero) were supposed to oversee 16 cognitive digital games such as *Bingo, Puzzle*, a calculation game, as well as an exercise where participants were supposed to remember a route taken by Silbot on a checkered floor and walk it. The following is an excerpt from an article explaining some of the challenges the Danish staff faced with the technology transfer. At first the citizens were rather unimpressed by the robot, but eventually they began to engage with it.

"There were actually several who said they thought SILBOT was not important. Then I confronted them and asked them: 'Well, you said SILBOT was unimportant. So why did you then walk over and said 'have a nice weekend' to it?'" (Line, nursing home staff) (Hasse 2015a).

Staff and citizens treat Silbot as they would each other - greeting it politely. Before it came to this cordial relationship Silbot had to be reconfigured in order to take part in the amalgamations formed at the rehabilitation center. The problem was that the robots' brain training program developed in South Korea was directly translated into Danish. This translation turned out not to fit the cultural context of the Danish rehabilitation center and its citizens. In the direct translation the 'teacher' seemed to speak clear Danish, but when the robot was put to use at the nursing home, Silbot was perceived to be rude, and in need of a lesson in politness. It scolded users for not getting the answers right in their brain training exercises. Robots as artefacts are not carriers of culture. It was in the meeting with the local cultural ecology that the healthcare staff's expectations of how a robot teacher should, or should not, address citizens emerged. Here Silbot was conceived as very rude and demeaning that had to be stabilized through re-programming.

"It's been reprogrammed after it has come to Denmark. It is not as angry, hard and cold anymore as when it came. In Korea you have a winner and a loser. So, it's a completely different culture. It has been programmed in a different way because it simply scolded the participants when they answered incorrectly. It had a completely different cultural approach to learning than we use in Denmark," Erica explains (nursing home staff) (Hasse 2015a).

In his thorough study of the diverse cultural receptions of Silbot in Denmark and Finland, Lasse Blond concludes that: "The recipient culture is constantly changing and at stake in the adaptation of Silbot." (Blond 2019, 211)

6.2 Meso-level organization of development

In Schumpeterian perspective (Schumpeter 1942), in a capitalist economy with unfettered competition, the capability to innovate is of vital importance to any firm. As such, in the long run, the primary source of the competitive advantage of a firm is its current stock of technological knowledge, its capability to acquire and create novel knowledge, and its ability to commercially exploit that knowledge in innovation (Kogut & Zander 1992). Given the technological developments by head-on rivals or research institutes in the same, related, or yet unrelated sectors, firms have to monitor, screen, filter, acquire, and put to use technological knowledge from outside the firm into new products or services. This also holds for the robotics sector and regardless of whether that focal firm is an established robotics firm active in building robots for the mature sectors (e.g. manufacturing, warehouse logistics) or rather a small entrepreneurial firm getting started with research and development of experimental robots for new sectors (e.g. agriculture, healthcare). After all, the focal firm may either need to preempt or at least timely follow rivals innovating their robots, or to create and enter a (new) market with a new type of robot. Moreover, also the sectors of customers are evolving subject to process innovation, such that the requirements and specifications may well change. Here, it is discussed how firms access and acquire new knowledge, how characteristics of such knowledge affect the mode of governance (buy, make, or collaborate), how this thus spans an innovation network, and how such an innovation network evolves over time.

6.2.1 External sources of technological knowledge

Over the course of researching, developing, designing, and adapting an entire robot, or systems or components used therein, robot developers may seek access to robot technology and underlying knowledge produced by other robot developers, possibly residing at another firm or institute. Generally, however, most of such (new) technological knowledge is not a 'public good' that is freely accessible and easily acquired to (competing) developers. Instead, access to new technological knowledge is often limited, possibly deliberately restricted (which is possible if knowledge is a 'private good'), and, in fact, robot developers may even be unaware of the very existence of particular technological knowledge. Moreover, access to and the ease of knowledge transfer depends on the capabilities of the actors involved. Given the scope, this publication gives just a brief overview of the most common issues in accessing, transferring, absorbing, using, and developing new technological knowledge.

First, even if a robot developer is aware of and has (unrestricted) access to technological knowledge related to the developments undertaken, the developer may have a limited **absorptive capacity** (Cohen & Levinthal 1990), i.e. a limited ability to immediately understand and use external technological knowledge. In part, absorptive capacity relates to fit of the field of expertise and the associated mental (ontological) framework of an individual developer and the elements of the technological knowledge sought to acquire. There are several ways to increase the absorptive capacity, e.g. conducting research in adjacent technological fields to expand the ontological framework, collaboration with those that do comprehend the focal technology and can thus explain relationship with concepts that are already understood, etc. Note that the concept of absorptive capacity is used at different levels of aggregation, e.g. the collective of employees jointly also span the absorptive capacity of a firm.

> **Absorptive capacity:** *A concept expressing the (often limited) ability of people (e.g. engineers) to comprehend and use external, new technological knowledge entirely.*

Second, in case of (radically) new technology, much of the technological knowledge is tacit (i.e. implicit, unexpressed) rather than codified (i.e. stored and easily transmittable, e.g. in documents), and the operational principles and internal mechanisms of the technology are understood almost exclusively by the primary developers. This complicates transmission and acquisition of technological knowledge. Direct, verbal, and preferably face-to-face communication is crucial, particularly when the new 'alien' knowledge sought to acquire and absorb is still largely tacit (Nonaka 1994). This is the case, for example, in the early stage of development of breakthrough technology; source and receiver of knowledge may have a substantially different understanding of the operational principles used, the receiver may have crucial omissions in its ontological framework of the technology, etc. Importantly, due to the tacit nature of knowledge as well as the efficiency of absorption of knowledge, there are substantial advantages of co-location of research & development activities in technology clusters/ regions.[4]

> **Co-location / face-to-face communication of tacit knowledge:** *Observation that tacit knowledge is best communicated in face-to-face communication. Actors engaged in processes requiring frequent exchange of such knowledge best co-locate for efficiency.*

A REELER case study on a harvest robot (SANDY) revealed that a further refinement is to be made. In this case, a particular early-stage design from a previous project was adopted. Like argued before, robot developers sought to improve particular crucial components (a specific sensor-actuator combination) which also required frequent field tests. In this case, the actor engaged in development of that sensor-actuator combination and the firm at which the pilots were run were in close geographical proximity. As, however, the robot design was already modularized, the work on other modules took place by partners further away and meetings with them

4 Note that there is a variety of other advantages as well such as a shared pool of skilled workers, attraction and development of specialized suppliers, sharing of knowledge platforms such as universities, etc. The interested reader is referred to literature on the so-called Marshall-Arrow-Romer externalities.

were infrequent (see discussion of the distributed character of technology in *4.0 Ethics Beyond Safety*). So, whenever the product design has been modularized, firms may work on separate modules relatively independently and geographically apart. Whenever the performance of technology is inhibited by the architecture itself or by poor interaction of modules, intensive collaboration and thereby geographical proximity is commendable.

Collaborative governance form: *Given the market failure for and the uncertain, temporary value of knowledge, firms prefer collaboration in exchange and creation over market transactions ('buy') and vertical integration ('make').*

Third, particularly challenging in the acquisition of technological knowledge is that there is, in general, a market failure: the actual price of knowledge can only be determined when the acquiring actor actually knows and understands it, but that effectively takes away the necessity to engage in the transaction in the first place.[5] As such, firms cannot acquire the knowledge on the market. Moreover, developing knowledge fully in-house is not particularly efficient, if possible at all, and replication is not efficient from an industry-perspective either. More importantly, once valuable knowledge has developed, the knowledge can be leveraged as a bargain chip in absorbing and accessing knowledge of others. As such, collaborative knowledge development seems the preferred governance form (Grant & Baden-Fuller 2004), which may take the form of supplier-buyer partnerships, outsourcing agreements, joint research projects, cross-selling arrangements, franchising, etc. Moreover, as firms have their own fields of expertise and would like to 'shop around' what other firms have to offer now or in the future, firms are generally hesitant to vertically integrate into corporate activities upstream or downstream. The need to shop around is also closely related to the technological and market uncertainty discussed before. Indeed, in many cases, firms would and should prefer a collaborative governance form, both in exploring potential fruitful knowledge exchange as well as in actual co-creation of innovative technological knowledge. That said, it does happen occasionally that established firms acquire specialized entrepreneurial firms to incorporate research capabilities and innovative knowledge. Similarly, it does also happen that established firms create spin offs of specialized activities that may be more likely to flourish when ran as independent firm (see e.g. the Story from the Field telling the story of the robot EULA, section 4.3.1). Note that while knowledge sources external to the firm are valuable in new product development, they are mostly used for access, idea generation and cross-fertilization. Firms' own internal production and technological knowledge is required for further problem solving (*see Kuwashima 2012* for a historical overview) and the development and production of the new product.

5 Arrow's information paradox, see Arrow (1974) and Grant (1996).

Free-rider problem: *Whenever everyone can use new knowledge for free, nobody is willing to invest in research and development, such that, consequently, the amount invested in research and development is (too) low.*

Last, knowledge developed by one actor may *spill-over* at no or relatively low costs to other actors. The latter actors thus *free-ride* on the investments of the earlier. Such spill-over free-riding is a disincentive to conduct research and development and a classical argument in favor of R&D subsidies. In this view, basic research has to be financed by the government, e.g. by grants to public universities and research institutes.

Means for value appropriation: *Ways for actors to ensure capturing the monetary rewards for conducting research and development of technology, e.g. patents, secrecy, branding.*

While particular types of inventions may be feasibly kept secret (e.g. a production method, software that can be obfuscated, a chemical formula), other inventions can be reverse engineered easily. Particularly for the latter, commercial firms (may) seek alternative measures to appropriate value of their intellectual property,[6] e.g. by means of patents, trademarks, marketing, rapid upscaling, or relentless innovation. Most important are patents, which from an economics point of view, guarantee a temporary knowledge monopoly and also disclose the knowledge in the freely accessible patent document.

6.2.2 Innovation networks

As already outlined, innovation economists argue that firms are engaged in an ongoing technological competition (generally alternating between product and process innovation over consecutive lifecycles, *see section 3.4.1*), which makes the ability to absorb, access, and create new knowledge paramount to their survival. Until the mid-1980s, the dominant paradigm for firms' strategic management was based on cost and price competition. Firms generally behaved as adversaries and were engaged in head-on competition. New product development was conducted mostly *internal* to the firms. In the 1980s, the resource- and competence-based perspectives emerged (Barney 1991), which stressed that a firm's sustained existence derives from having unique, hard-to-imitate, durable capabilities *making it an attractive, competitive supplier.* Indeed, firms should be striving to remain a favorable supplier by innovating. To this end, firms should specialize on and leverage the core competences, whereby a certain degree of vertical specialization is both efficient, reducing risk, and allows 'shopping around' for complementary knowledge. This gave rise to vertically specialized firms connected in supply *networks*. Moreover, to a certain extent, the firms in these

6 This leads to both a temporary monopoly and an efficiency problem which cannot be solved simultaneously.

networks have a common interest: providing a commercially interesting product or service to the final customers or end-consumer.

With progressive vertical specialization, though, the organization of research and development activities becomes challenging. The previous section highlighted several impediments to accessing, acquisition, diffusion, and creation of technological knowledge purely due to the characteristics of the underlying knowledge and humans as its vehicle. Particularly acquisition of new knowledge (and hence diffusion) does not occur spontaneously, but firms need to create channels for knowledge exchanges with other economic actors, generally based on direct compensation but more often based on a certain level of reciprocity. Ultimately, these R&D collaborations span innovation networks. (*See e.g. Hagedoorn 2002* on the rise of collaboration in research and development.)

Such innovation networks may well be different from the supply networks used for the manufacturing of existing products or provision of existing services. Whenever firms engage in new product development projects, they may indeed involve current suppliers or customers because of their specialized knowledge (and innovation capabilities) or to ensure future compatibility and/or manufacturability. However, in new research and development projects, firms may also break away from existing relationships (Rosenkopf & Padula 2008) and involve new partners, not only new firms, but also research institutes, cooperatives, etc. So, the innovation networks may well be more heterogeneous than production networks, may contain actors with competences far from production, and may have a structure quite different from the technological decomposition of the product. In publicly funded research, this is not uncommonly the case. Moreover, such innovation networks may be rather fluid and feature relationships that are severed whenever exploration does yield not leads for further collaboration, relationships that are dissolved after exchanging and cross-fertilizing knowledge, and relationships that even turn into durable buyer-supplier ties in the emerging production networks. Notably, for an outside firm or research institute to get invited into an innovation network (either formally or, at first, informally), there have to be prior indications that the actor in question may be the provider of complementary, potentially innovative knowledge. Moreover, given the 'erosion' of the innovative value of knowledge once it has been used or competitors have presented something superior, actors are particularly considered valuable if they show to have the capability to create new knowledge that is again of value to partners in the future. Indeed, firms need to acquire and update capabilities to explore and isolate relevant knowledge outside the firm, then acquire and absorb that knowledge, and subsequently use that knowledge to alter current products and production processes (Verona & Ravasi 2003). In general, in many industries, firms are involved in dynamic, evolving innovation networks with collaboration across the globe (Liu, Chaminade, & Asheim 2013). Arguably, from this perspective, an indispensable capability for firms is to initiate or get into a relevant innovation network, manage local relationships therein, and timely extract and organize valuable product propositions. Do note, however, that also the structural properties and the location of particular actors in an innovation network determine access to particular (types of) knowledge and thus decisively shape the creative aspects of knowledge diffusion and creation (e.g. Vermeulen & Pyka 2017).

REELER ethnographic research revealed that the population of actors engaged in robot development is diverse and ranges from large, established firms that build industrial robots with modularized technology for mature industries, to specialized component developers researching and developing components like grippers, sensors, and software, to institutes doing fundamental research on modules or rather applied research on experimental service robots, to small, entrepreneurial firms that seek to leverage particular technical capabilities to create new niches in healthcare, education, etc. As discussed in section 6.1.2, the robotics sector may be segmented by (the sector of) application. On the one hand, there are mostly large, established firms developing and building robots for use in manufacturing, automotive, warehouse logistics, etc. On the other hand, there are niches of (often) small, entrepreneurial firms (including start-ups and university spinoffs as well as business units of large established firms) engaged in research, development, and building (experimental) robots for application in agriculture, healthcare, education, construction, space, etc. Particularly for the latter 'niche creating' robotics firms and institutes, public funding is a major driver, notably because there are only few commercially viable applications, there are many technical challenges and demanding circumstances to resolve. Arguably, some of the robotics innovation networks studied are fairly typical for the early research stage of the robots being developed, i.e. requiring a substantial amount of analytical work. Much of the robot research and development took place in heterogeneous research projects with specialized actors with or without actual customers (e.g. SANDY, REGAIN), two-tiered business-to-business networks in which robot technology is either passed down after research at large research institutes or acquired on the market (e.g. WIPER, COBOT). Moreover, in some networks, there is a prominent role for universities (e.g. REGAIN, SANDY), knowledge institutes, and industry platforms (*see for examples 2.0 Robot Beginnings* and *3.0 Collaboration in the Inner Circle at www.responsiblerobotics.eu*). Some of the firms are small entrepreneurs seeking intensive collaboration with potential downstream customers and some firms are deliberately spun off of existing industrial robotics companies (e.g. COBOT, *see 4.0 Ethics Beyond Safety, section 4.3.1, the Story from the Field about the EULA robot*).

As mentioned in 4.0 Ethics Beyond Safety, EULA is the result of a technology first developed at the State Aerospace Centre (AC), then moved to the research department at the COBOT company which developed it to its present TRL9. Today, the robot is in mass production at the COBOT factory. The parts for the robot are delivered by different companies and subcontractors. For instance, the transmission equipment is from *Smooth Drive*, the motors come from *PS Systems*, and the sensors from *ReadyDrive*. Both *PS Systems* and *ReadyDrive* are spin-offs from the State Aerospace Centre. The rolling

bearings come from a Dutch company (*The Dutch Ball Bearing Company*) and a French company (*TXT*), and some of the other big bearing's companies.

In fact, the actors engaged in analytical/ science-based innovation activities (such as studying key parameters for interaction between physical parts, e.g. SANDY) are located in relatively close proximity, while the actors engaged in synthetic, engineering-based innovation and recombination of rather standardized components (may) collaborate at greater distance [7] (*see section 6.3.2 on the spatio-temporal patterns in collaboration*).

Staggered expansion: *Strategy to expand the group and type of stakeholders involved in specifying user requirements, and test/ pilot runs over the course of several new product development iterations. For example, first focus on stylized requirements defined in-house, then involve intermediaries, then involve lead-users, etc.*

Some of the REELER case studies revealed an interesting particularity, namely that during the development of types of robots, so-called intermediaries are involved as 'spokespersons', rather than the actual end-users of robots. In some cases this is problematic if managers speak on behalf of workers without knowing about their actual work life (*see 10.0 Meaningful Work*). However some cases involve both end-user as the final beneficiaries and for instance staff or physiotherapists as directly affected stakeholders (e.g. SPECTRUS and REGAIN), who become were involved in the early developments in order to explain what is needed on their side to make a robot work (thus in the end benefitting the patients). In case of the educational robot (ATOM), teachers were also to some extent involved together with the pupils. Arguably, over the various iterations of research & development, it is likely that both requirements and technical specifications become increasingly more concrete and fine-tuned to end-consumers. So, over the development process, it is well imaginable that robot developers first engage in development operating purely on the basis of assumptions about the user, then involve intermediaries (possibly in several iterations), and in the later stages start to fine-tune with the final users (possibly in several iterations). A word of warning of this '*staggered expansion*' strategy for obtaining user requirements, information on the environment of application, etc.: blind spots, biases, ignorance in the developers' assumptions on and the intermediaries' perception of these requirements may cause severe shortcomings in the actual use that are costly to resolve and had better been anticipated by earlier involvement of end-users in develop-test-plan cycles. Of course, the aforementioned 'dilemma of specification sequentiality' still holds: intermediaries and users ultimately need to see and use some test version or materialization of the robot to be able to refine and articulate the requirements.

6.3 Evolution of technology and society

As we have seen in the previous sections, robot developers are engaged in short- and medium-term processes of concrete robots development at the micro-level and exploration & exploitation of the network of innovation partners at the meso-level. On top of these short- and medium-term and partially firm-specific agendas for robot developers, the robotics sector goes through consecutive, medium- to long-term lifecycles each consisting of several phases. Due to the bouts of innovation activities particularly in the early phases of the industry lifecycles, there is a long-term, bursty accumulation of technology and scientific and engineering knowledge, which is created, altered, extended, and possibly dismissed over time and possibly across lifecycles. While technology progresses, firms in co-located (possibly technological specialized) clusters may either drive, follow, or fall behind on technological development. As such, there are long-term geographical shifts of sectoral activities. Moreover, at the same time, society is evolving, in part responding or anticipating the introduction of the focal technology, which reflects in concerns, market targets, institutional arrangements, etc. for developers to take into account. This section is devoted to these three long-term processes.

6.3.1 Industry lifecycle and spatio-temporal patterns in collaborative innovation

Over the course of time, most technologies are often incrementally improved or adapted to local use or culture. However, occasionally, a radical innovation brings about a substantial increase of performance in some key parameter(s), which causes a boom in product innovation activities to apply the focal technology in new areas, effectively starting a new technology lifecycle. According to the various industry/ product lifecycle theories,[8] the intensity and type of research & development of firms is contingent on the extent to which these firms have readily explored and exploited technological and market opportunities. In fact, there is an 'inception phase' of technology development during which there are many competing, innovative, and experimental technologies with large parts of the knowledge yet uncodified. Firms are primarily engaged in exploration. As such, they are likely to postpone irreversible investments to acquire *specific* technological knowledge and build *particular* technological capabilities. Due to an interlocking of gradual articulation of market preferences, the shake-out of product designs and technological ideas, crossing a tipping point in market uptake, favorable economies for production upscaling, etc., a so-called de facto *dominant design* emerges. In the subsequent 'mature phase', firms

7 Here, the distinction between analytical/ science-based knowledge (e.g. life sciences), synthetic/ engineering-based knowledge (e.g. food processing, automotive components, mechanical engineering) or symbolic knowledge (e.g. moving media) is used. See Asheim & Coenen 2005, Asheim & Gertler 2005, Amin & Cohendet 1999 Martin & Moodysson 2011.

8 The industry/ product lifecycle literature has its roots in seminal papers from the 1970s and 1980s; Utterback & Abernathy 1975, Anderson & Tushman 1990, Hannan & Freeman 1977.

targeting the main segment of the market adopt the dominant design. As of that moment, competition no longer revolves around product innovation anymore, but rather around price, market share, etc., inviting rationalization of production (and possibly thus further standardization and modularization of technology). This mature phase of an industry may persist for sustained periods of time, particularly in industries with natural monopolies, strong scale advantages, high infrastructure costs, barriers to entry, etc. However, in more competitive mature markets, whenever incremental product innovations have been exploited and the productivity gains of process innovation have been realized, the profit margins erode quickly. This stimulates firms to engage in research for radical innovation to open up new markets, sell radically new products at higher margins, and follow new business models. This is Schumpeter's celebrated notion of *creative destruction*. When demand materializes, competitors follow, thus unleashing competition in the inception phase of a new cycle.

Note that, in general, *incremental* innovation comes about by extending existing technology in steps *evident to experts in the same field.* Whenever research and development merely extend the current products, it is essentially consolidating the current technological paradigm. In addition, entrepreneurs seek to leverage previous research and increase the returns on investments. With that, there is a risk that, at some point, research & development becomes essentially *locked in* into a particular technological paradigm.[9] It might even be so that particular rationales for design choices made in the past are no longer relevant but market inertia hampers switching to (superior) alternatives (e.g. the QWERTY layout of keys once picked to prevent jamming of the mechanical typewriters (David 1985)). Technological formats, designs, etc. may also be 'fixed' by double-sided markets and network effects (e.g. the VHS versus Betamax versus V2000 competition on the Videocassette Recorder market). Essentially, a *lock-in* can only be escaped by radical technological research & development, which has several challenges of its own, such as the high risks of failure, the first mover disadvantages (e.g. making high costs in exploration, while competitors can be imitated cheaply), etc.

Incremental vs. radical innovation: *Two types of innovation. Incremental innovation concerns mere extensions of the existing design, consolidating the existing paradigm. Radical innovation introduces a new paradigm, generally a breakthrough increasing the performance in some dimension(s) in the order of several magnitudes.*

9 Interestingly, while predominantly large corporations may have resources for research & development, they seek to further exploit their own technological paradigms. In contrast, entrepreneurial startups and spinoffs may actually seek means to overthrow the paradigm of incumbents. From an evolutionary perspective, a 'decentralized search' by a multitude of entrepreneurs, each searching within its particular technological space, exploring own ideas may decrease chance of industries getting locked-in.

Over the course of the lifecycle, the population of firms (consisting of both incumbents and entrepreneurs freshly swarming in) thus has evolving innovation targets. With that, also the collaboration propensity and (preferred) governance forms in innovation activities change (e.g. Afuah 2001). In the turbulent inception stage, entrepreneurs explore and experiment with product technology and as such rather stay vertically specialized to flexibly switch between potential upstream and downstream partners. In the mature phase, firms focus mostly on scale and low-cost production and incremental process innovation takes place mostly within the existing supply/ production network (e.g. Rosenkopf & Tushman 1998). The governance forms of firms in and dynamics of the production network is out of scope of this publication chapter.

6.3.2 Regional clusters, catching-up and falling behind

Given the changes over the industry lifecycle of the type of innovation activities (from product to process innovation), the shifts in the characteristics of knowledge (from tacit to more codified, from 'alien' to 'familiar'), it may well be so that also the governance form of collaborations and dynamics and structure of the innovation network changes over time. Indeed, apart from *temporal* patterns, there also are particular *spatial* patterns to be expected. Particularly during the inception stage of industry lifecycles and, more importantly, with the rise of the industry, much of the technological knowledge is still tacit, partial, fragmented, etc., such that face-to-face communication and intensive collaboration within geographical proximity may well be preferred. That said, the combination of knowledge for (breakthrough) product innovation is generally new rather than yet another incremental combination from likely knowledge sources. As such, knowledge is discovered and accessed from outside the existing network and possibly even outside the region in which the focal firms reside. If such alien technological knowledge is not found in the region/ cluster, it must necessarily be imported from a different region / cluster, imported through a pipeline and absorbed and used in a local buzz (Bathelt, Malmberg, & Maskell 2004). Subsequently, product designs emerge, knowledge becomes codified and embodied in products. With that, face-to-face communication and thereby co-location for exploitation and extension of that knowledge base is no longer strictly required (Audretsch & Feldman 1996).

(Spatio-)temporal patterns: *Notion that type of research and development changes over the course of the industry evolution, notably cycling through breakthrough, exploration, design dominance, and exploitation phases. Moreover, also the location of research and development activities as well as the distance over which collaboration takes places may change over time.*

This spatio-temporal pattern is, however, somewhat theoretical as there is, arguably, a strong moderating effect of the build-up of a population of actors (in one or competing pro-

duction/ innovation networks), skilled labor pool, and collective knowledge base in a particular region, which is well-likely a gradual process. A prominent strand in innovation economic literature studies the geographical aspects of innovation and reveals how regional economic forces and externalities moderate the spatio-temporal patterns of innovation networks.

First, there are regional agglomeration externalities. By co-locating in the same region, firms within the same and technologically related sectors have access to a shared pool of skilled labor (which moves or already lives there or is provided by local education institutes), find specialized component suppliers (which also move to or rather emerge in the regions), and enjoy knowledge spillovers by mobility of personnel, informal contacts, etc.[10] Regarding the latter point, for reasons given before, co-location allows efficient absorption and creation of new technological knowledge (Asheim & Coenen 2005). While firms may thus actively move to particular regions to tap into knowledge, access the labor pool, etc., an additional cause of clustering of technological development is that spin-offs often stay close to the parent company,[11] and, similarly, academic start-ups may well stay close to the university.

REELER studied patent data and finds clear support for the agglomeration of robotics inventors in Europe: there is a particularly strong geographical clustering in several Baden-Württemberg and Bayern regions in the south of Germany, (*see Figure 6.2.*) Interestingly, these clusters seem to host innovation networks around competing system integrators or competing lead users. This is actually supporting the claim that agglomerating externalities are at work.

Note that regions may host a mix of firms developing robots for different market segments (e.g. manufacturing versus healthcare), may host firms from the apply sectors or not, etc.

That said, another REELER study revealed that countries may well be 'technologically specialized' in particular types of robots; while most countries have patents associated with robots for the (car) manufacturing sector, for instance, The Netherlands is specialized in robots for the agricultural sector (Spinoni 2018).

Second, although there are particular advantages of co-location (i.e. geographical proximity), the knowledge does only travel through channels. Indeed, there are still institutional or organizational ties required for the creation of channels for the exchange of technological knowledge (Boschma 2005). REELER case studies and also the REELER mini-public on agricultural robots revealed that robot development takes place in particular 'hotspots', with the consequence that access to technological knowledge may well be limited to actors in other parts of the world. It was, for instance, found that access to technological knowledge on agricultural robots is limited on the African continent (*see Annex 5 REELER Outreach Tools*)[12]. As such, innovation networks in regional clusters in developing countries may compensate the lack of particular knowledge, resources, and capabilities by nurturing a more global innovation network (Ernst 2002).

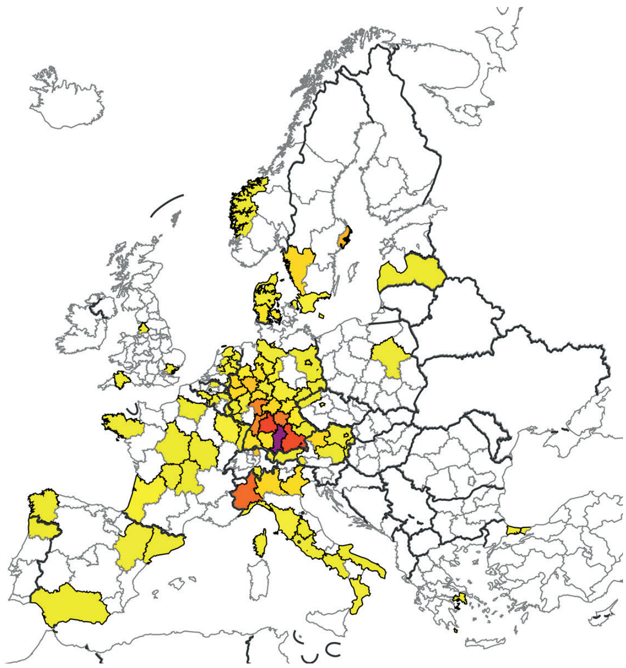

Figure 6.2. Density of the NUTS2 location of inventors patenting robot technologies (REGPAT data until February 2016). A darker shade means more inventors mentioned in patents are located in that particular NUTS2 region. A region is blanc if no inventors were registered in the REGPAT data. (Source: own data extraction and visualization, see responsiblerobotics.eu/annex-1)

Third, while breakthrough innovation initiating a new lifecycle generally requires 'alien' knowledge that often comes from 'outside' (at least outside the cluster, but well possibly also outside the region). That said, knowledge may also be acquired for mere application, such that knowledge transferred into the region need not necessarily target a breakthrough. A study of one of the REELER researchers (Vermeulen 2018) found that the distance to the ultimate sources of technological breakthrough knowledge increases over time, but collaboration of co-inventors in further development becomes increasingly local. The increasing distance of referenced knowledge sources is facilitated by, firstly, codification, and, secondly, diffusion. Before researchers and developers can access knowledge over longer distances, it is to be codified in patents, papers, presentations, embodied in products, etc. Moreover, time is needed for inventors, developers, and researchers to become aware of the existence of new knowledge, i.e. there is diffusion of information on the existence of knowledge. Note that, even if it is the (technological) knowledge itself that dif-

10 These are the Marshall-Arrow-Römer externalities, see e.g. Glaeser, Kallal, Scheinkman, & Shleifer 1992.

11 There is an emerging body of literature revolving around some hypotheses of Klepper, see e.g. Berchicci, King, & Tucci 2011.

12 see responsiblerobotics.eu/annex-5 and see responsiblerobotics.eu/outreach

fuses, there are formal and unwritten rules that references are to be made to the original source (e.g. patent citations, paper references). The increasingly local collaboration of researchers and developers is due to 'technological localization' (*see also Section 6.1.3* on technology transfer), i.e. the increasingly applied character of technological extensions, integration with existing technology, adaptation to local environments (e.g. in terms of language, culture, practices, beliefs, etc.), catering to local market preferences, technological appropriation, etc.

Fourth, the development of a region/ cluster may be 'path dependent'; knowledge development is cumulative and follows particular technological trajectories. Search directions and hence new discoveries are both deliberately as well as unintentionally extending existing technology (by recombining knowledge that is known), building upon a certain technological paradigm (Dosi 1982). Such that *path-dependency* in technological knowledge development happens to both individual inventors, to companies, as well as clusters and regions. Whenever firms experience dwindling profits, decreasing demand, etc., they may seek to enter new markets or even engage in radical innovation to create a new product-market (*see section 6.3.1*).

Path dependency: *Tendency of new technological knowledge to build upon and be compliant with the extant, surviving technology paradigm.*

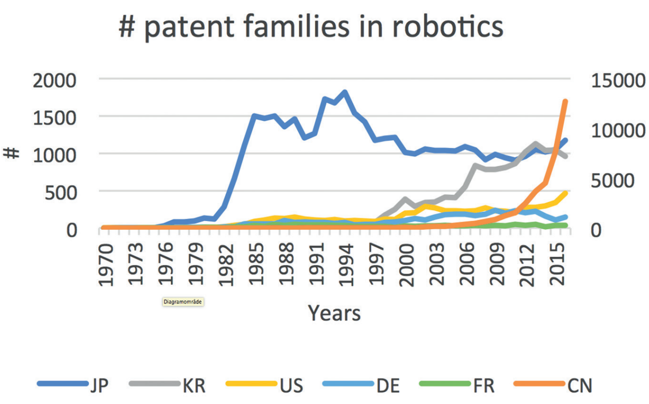

Figure 6.3. Number of patent families in the PATSTAT dataset. The scale on the right axis applies to the number of Chinese (CN) patents, while the scale on left axis applies to the number of patent families of the other countries. (Source: own data and elaboration, see responsiblerobotics.eu/annex-1).

Due to path dependencies, resistance to innovation, and technological lock-in, clusters may fail to keep up or untimely see the urgency to do so, thus falling behind competing clusters. Famous examples are the Detroit and Ruhr areas. On top of that, there is structural change in the sense of 'de-agrarization' and 'deindustrialization', such that particular clusters are bound to be dissolved. That said, while there was a substantial amount of patenting of robotics inventions, particularly by Japan, USA, and Korea in the past, but nowadays this is completely eclipsed by a surge in the number of Chinese patents, (*see Figure 6.3*). Although it remains to be seen whether these patents are part of a 'thicket' to obstruct rivals or actually lead to innovations, it is clear that China is accumulating knowledge and competences that may constitute a threat to the traditional clusters in Japan, South-Korea, the U.S.A., and Germany.

6.3.3 Technological change and social construction

This chapter has focused mostly on the process of technological development from the perspective of either the robot developers or robotics company, thereby implicitly assuming the stakeholders and notably customers, but also society in general, have relatively fixed, immutable albeit unknown requirements. So far, the agenda of research & development activities of robot developers was largely determined by the goals of product development, defined by the technological role in innovation networks, and as has just been introduced, the (bursty) accumulation of technology in the robotics(-related) sector(s) over the course of the consecutive industry lifecycles. However, particularly over the long-term, there may be considerable changes in requirements of customers, the application environments, expectations and (public) opinions of stakeholders, the institutional and infrastructural arrangements, legal and ethical conditions, policy instruments in place, etc. So, society evolves and in part even due to the introduction of the focal (and possibly impactful) technology.

Economists started out picturing technological change as a process in which technology was first invented ('new to the world'), then innovated (i.e. tailored to commercial use in a particular, new market), and then diffused (i.e. spread across both producers and consumers through imitation). Similarly, it was pictured as process in which academics conceive scientific concepts (fundamental research), developers subsequently materialize these concepts into technology (applied research), and entrepreneurs finally bring the technology embedded in products to the market. Gradually, economists refined this perspective by moving away from a process with discrete, consecutive stages, to an involved, non-linear process in which experiences with application or actual use feeds back/ forward to innovation and invention activities, e.g. adapting the technology or leading to new product developments. In some cases, entrepreneurs initiate research & development because there is a clear market demand (e.g. medication and treatment of diseases), i.e. there is market pull, while in other cases, entrepreneurs 'push' technology and rather create a new market (cf. Steve Jobs' supposed quotation "A lot of times, people don't know what they want until you show it to them").

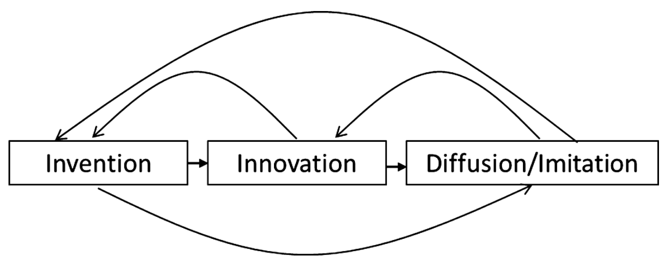

Figure 6.4. Non-linear model of technological change

Similarly, there is a non-linear relationship between basic and applied research. Basic, fundamental scientific research conducted at universities and public research institutes does not necessarily precede applied research undertaken by companies. History is littered with examples in which the scientific understanding was developed only after practical applications emerged or were even well-established (e.g. the steam engine was widely used before thermodynamics was understood).

Such long-term technological change and evolution of society and the economic system is (also) the domain of scientific fields like the history of technology, and science technology and society studies (STS). For instance, how harnessing electricity generation and transmission led to (i) emergence of public utilities, (ii) sectors for home appliances, machinery, tools, etc., (iii) electrification of buildings and the public space, (iv) development of a wide range of other technologies and enabled a multitude of new services, (v) radical changes of work, recreation, and leisure, (vi) opened up new scientific fields and changed others. While it remains to be seen whether robot technology will be this impactful, it may also lead to various new sectors, permeate daily life in households, factories, offices, public space, etc., enable providing new services, radically change work and recreation, etc.

In fact, it may be argued that robotization of society is part of the techno-economic paradigm (Kondratiev wave) started in the 1980s (Perez 1985) with -in retrospect- a cascade of innovations based on microchips, software platforms, mechatronics (i.e. the fusion of mechanics, electrical engineering, and embedded software), digitalization, communication technologies including internet, etc. Arguably, at present, there is a wave of further technological recombinations leading to interactive robots, artificial intelligence, block chain, Internet-of-Things, etc. which are applied in a range of sectors under headers such as Industry 4.0, Agriculture 4.0, Healthcare 4.0., etc. The introduction of these technologies brings new business models, requires new institutional arrangements, upsets social and economic conventions, etc. Moreover, new application concepts also feed back into design requirements. For robot designs, this goes as far as progressive integration in complex socio-technical environments requiring sophisticated interaction with humans (e.g. reading facial expressions, predicting movements, speech recognition), advanced technical interoperability (e.g. communication protocols, data recombination, flexible information systems, swarm robotics), comprehension of complex, variable, and ill-structured environments, etc.

As outlined in section 6.2, modern innovation economics distances itself from any linear, hierarchical, deterministic view. Instead, it perceives technology development taking place by knowledge-based collaboration of a heterogeneous network of entrepreneurs, research institutes, government, pressure groups, and other types of economic actors. Such innovation networks evolve endogenously over time, with autonomous actors entering, refocusing, and exiting, hereby also driven by emergence, maturation, transformation, and dissolution of their segments, etc. Moreover, activities of robotics firms are affected by the competitive nature of the industry.

Ambitious (prospective) robot developers, may well not only be considered how such (big, long-term) changes affect their immediate research, development & building activities, but they may also be motived by their contribution to the betterment of society and may in fact actively market themselves so. Moreover, not only the market but also funding agencies may reward such a 'socially responsible' attitude. From a meta perspective, Horizon 2020 funded projects such as REELER and INBOTS to study how to enhance the socially responsible and ethical design of robots (Perez 1985).[13] Both projects seek to do so largely by advocating for, raising awareness on, and providing tools to incorporate societal concerns in robot design and application.

6.4 Concluding remarks on Innovation Economics

In conclusion, this chapter analyzes the process of researching, developing, and designing robots over short-term 'new product development' processes within endogenously evolving innovation networks facing industry lifecycle challenges, long-term technological change, and a changing society.

We adorn a stylized new product development method, notably recognizing that robot developers have to (i) sequentially 'bootstrap' out of a situation fraught with market and technological uncertainty, (ii) modularize robot designs and iteratively and recursively solve technical bottlenecks therein, and (iii) conduct repeated develop-test-plan cycles thereby possibly extending the set of stakeholders involved over time in a staggered fashion. Moreover, often, robot development is done by a group of roboticists distributed over economic actors across space and time. In this, the roboticists have to cope with limited control over the, generally, decentralized development process, artifacts passed down without context, etc. In addition, these roboticists are restricted by the resources, capabilities, and boundaries of the firms and institutes employing them as well as the nature of the possibly relatively durable, (in)formal relationships of these actors. Conversely, resources are mobilized, capabilities developed, and relationships established on the basis of robot developers' current vision, technical challenges, etc., which are themselves outcome of previous activities. As such, there is co-evolution of technical specification and materialization of user requirements, and the innovation network spanned by the collaborating economic actors. Given the risk of thus getting technologically locked-in, innovation theories are emphasizing the significance of exploration of technical solutions as well as potential partnerships.

On top of these short-term micro-level and medium-term meso-level determinants of research, development, and design decisions, there are various long-term determinants as well. After all, there are consecutive industry-wide lifecycles pacing

13 INBOTS (http://inbots.eu), a Horizon 2020 funded research consortium, is developing and promulgating a framework for socially responsible robotics.

product and process innovations driving scattered accumulation of technologies as well as growth and diversification of sectors of application.

In fact, in addition, at the meta-level, there is scientific progress on new product development methodologies, emergence of strategic management and innovation management paradigms, and progressive insights in societal aspects and human factors to be taken into account (e.g. human-robot interaction), etc. Arguably, REELER is actually contributing to the latter by imploring robot developers to now also properly include a wider circle of stakeholders and incorporate ethics in design considerations (beyond the usual safety, security, liability, ergonomics, etc.). Hopefully this chapter also showed that we are well-aware of the (fundamental) challenges robot developers face and provided conceptual ideas on how to cope with them.