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Industry report

The Digital Innovation System of the Dutch Processing Industries

An overview of diffusion processes and barriers to digital innovation in the processing industries of the Netherlands

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Summary (Nederlands)

Digitalisering is een belangrijke sleuteltechnologie die grote gevolgen heeft voor verschillende sectoren, waaronder de energie-intensieve procesindustrieën. Verwacht wordt dat de impact van digitalisering niet alleen techno-economisch zal zijn, maar ook de duurzaamheid van industrieën zal beïnvloeden. De verwerkende industrie in Nederland lijkt aan het begin te staan van een snelle digitale transformatie. Een aantal toepassingen van digitale technologieën zijn relevant voor de procesindustrie, met name voor energie-efficiëntiedoeleinden. Deze omvatten analyse van activabeheer, analyse van energiebeheer, geavanceerde procescontrolesystemen en digitale tweelingen. Een scala aan actoren, bedrijven, netwerken en instellingen (waaronder TKI Energie & Industrie) houdt zich bezig met activiteiten die bijdragen aan de ontwikkeling en verspreiding van digitale innovatie. In deze studie worden de belangrijkste toepassingen en actorengroepen op het gebied van vraag, aanbod, bemiddeling en beleid geïdentificeerd. Met name de aard van digitale innovatie, de omringende nieuwe bedrijfsmodellen en de opkomst van nieuwe soorten bedrijven hebben geleid tot een bijzonder complexe aanbodzijde.

Om systematisch de activiteiten te identificeren die bijdragen aan de acceptatie van digitale toepassingen door eindgebruikers, zijn vijf stadia in het acceptatieproces van innovaties gedefinieerd. De eerste fase is wanneer de eindgebruikers voor het eerst in aanraking komen met de digitale innovatie. Deze blootstelling kan afkomstig zijn van interne teams binnen eindgebruikers, start-ups en technologieleveranciers, kennisnetwerken, consortia, leergemeenschappen of zelfs van bedrijven buiten de procesindustrie. De tweede fase is overtuiging, waarmee legitimiteit voor de technologie wordt gecreëerd. Zo kunnen er pilots en demonstraties plaatsvinden, die kunnen leiden tot aanzienlijke technische verbeteringen en veranderingen. De derde fase is de besluitvorming, waarbij de betrokken actoren beslissen om al dan niet door te gaan met de implementatie. De vierde fase is de implementatie, waar de eindgebruiker de technologie begint te gebruiken en er veel leren plaatsvindt. De laatste fase is wanneer de beslissing wordt genomen over het al dan niet blijvend gebruiken van de digitale technologie en het identificeren van mogelijke schaalvoorwaarden.

Vervolgens identificeert de studie negen sociaal-technische belemmeringen voor digitale innovatie die in de verschillende adoptiefasen kunnen ontstaan. Dit zijn (1) verschillen in prikkels tussen teams en hiërarchieën, (2) besluitvormingsuitdagingen voor *bottom-up* digitale innovaties, (3) afstand tussen geavanceerde innovatie en de werkvloer, (4) zorgen van IT-teams en een meer algemene angst voor algoritmen, (5) ontbrekende digitale infrastructuur, (6) job-rotatie en het verlies van innovatiekampioenen, (7) *skills*-gerelateerde uitdagingen, (8) schaal-gerelateerde uitdagingen en (9) partnerschap-gerelateerde uitdagingen.

De gestructureerde aanpak in vijf fasen die in dit onderzoek wordt gepresenteerd om (het gebrek van) verspreiding van digitale innovatie te begrijpen, kan door beleidsmakers en andere betrokkenen worden gebruikt om de innovatielevenscyclus van een technologie te volgen. De negen geïdentificeerde sociaal-technische barrières richten zo de aandacht van de industrie op onderliggende problemen die meerdere digitale technologieën belemmeren. Het wegnemen van deze barrières kan de prestaties van het digitale innovatiesysteem van de Nederlandse verwerkende industrie aanzienlijk verbeteren. Toekomstig onderzoek zou zich moeten richten op het identificeren van “systemische” beleidsinstrumenten die kunnen worden gebruikt om deze onderling verbonden barrières te overwinnen.

Summary (English)

Digitalization is an important key-enabling technology that significantly impacts various sectors, including the energy-intensive processing industries. It is expected that digitalization's impact will not only be techno-economic, but it will also influence the sustainability of industries. The processing industry in the Netherlands seems to be at the beginning of a rapid digital transformation. A few main categories of digital technologies are relevant to the processing industry, particularly for energy efficiency purposes. These include asset management analytics, energy management analytics, advanced process control systems, and digital twins. A range of actors, firms, networks, and institutions (including TKI Energy & Industry) engage in activities contributing to digital innovation development and diffusion. The key actor groups on supply, demand, intermediation and policy have been identified and linked in this study. Notably, the nature of digital innovation, the surrounding new business models, and the emergence of new types of firms have resulted in a particularly complex supply side.

To systemically identify the activities contributing to the adoption of digital technologies by end-users, five stages in the adoption process of innovations have been defined. The first stage is when the end-users get initial exposure to the digital innovation. This exposure can come from internal teams within end-users, start-ups and technology suppliers, knowledge networks, consortia, learning communities, or even from firms outside the process industry. The second stage is persuasion, where legitimacy for the technology is created; pilots and demonstrations can take place, which could lead to significant technical improvements and changes. The third stage is decision-making, where the actors involved decide whether or not to go ahead with implementation. The fourth stage is implementation, where the end-user begins to use the technology, and significant social learning takes place. The final stage is when the decision is made on whether to continue using the digital technology and identify possible scaling conditions.

Next, the study identifies nine overarching socio-technical barriers to digital innovation which could emerge in the different adoption stages. These are (1) incentive differences across teams and hierarchies, (2) decision-making challenges for bottom-up digital innovations, (3) disconnection of cutting-edge innovation with the shop floor, (4) concerns of information technology teams and a general fear of algorithms, (5) lacking digital infrastructure, (6) job rotation and the loss of innovation champions, (7) skills-related challenges, (8) scale-related challenges, and (9) partnership-related challenges.

The structured five-stage approach presented in this study to understand the (lack of) diffusion of digital innovation can be used by policymakers and practitioners to trace the innovation lifecycle of a technology. The nine socio-technical barriers identified can direct the industry's attention toward underlying problems that hinder multiple digital technologies. Overcoming these barriers could significantly improve the performance of the digital innovation system of the Dutch processing industry. Future research should focus on identifying "systemic" policy instruments that can be used to overcome these interrelated barriers.

Contents

1 Introduction

Digitalization is an important key-enabling technology that greatly impacts various sectors, including the energy-intensive processing industries. It is expected that digitalization's impact will not only be techno-economic in nature but will also influence the sustainability of industries.

In the Netherlands, the processing industry is considered a crucial part of the Dutch economy and society. Advancing these industries through innovation is of high strategic importance to advance sustainability and the competitive position of the Netherlands. Digitalization, mainly focused on energy efficiency technologies, has therefore received much attention in this regard. In recent years, a unique initiative as part of the TKI Energy & Industry has emerged in the industry centred around digitalization and the vision of industry 4.0. The initiative includes a variety of innovation projects, partnerships, start-ups, roadmaps, and even internal transformations of firms in the industry. These activities, coordinated or uncoordinated, have contributed to the development of a "digital innovation system" within these industries.

The starting point in understanding the concept of innovation systems is that the emergence of any innovation is complex (non-linear), and it does not occur in isolation. An innovation system comprises various actors (people, firms, and networks) and processes responsible for the development, diffusion, and use of an innovation. Using the concept of an innovation system allows us to have a clear overview of what is going on in the ecosystems of innovations and further help identify any current systemic problems.

There is currently no systematic understanding of the digital innovation system for the Dutch processing industries. Particularly, what is unclear is how potential energy-saving digital technologies are currently spreading throughout the industry. It is important to identify the actors and technologies involved as well as how the matchmaking between suppliers and end-users occurs. A well-functioning digital innovation system will allow for effective matchmaking; therefore, it is crucial to identify the system problems hindering this adoption.

The overall aim of the study in this report is to address the aforementioned knowledge gap. Identifying and analyzing the digital innovation system will allow us to find ways to effectively support and stimulate the actors and processes or overcome any persistent barriers to innovation. The research objectives of this study are as follows:

- Provide an overview of the types of suppliers, providers, customers, and matchmakers of digital technologies in the Dutch processing industry and the forms of these digital technologies (Section 2).
- Identify the activities that contribute to the adoption of digital innovation, thereby linking the supply and demand of technologies (Section 3).
- Identify the most pressing problems or barriers in this digital innovation system (Section 4).

The primary data source in this study is expert interviews. The analysis is based on semi-structured interviews with 25 industry experts, including various managers, innovators, founders, researchers, and consortia actors within the Dutch processing industry (see Appendix). Secondary data sources include firm and consortia websites, as well as industrial reports that are cited at various points of the analysis.

2 The System Structure of the Digital Innovation System in the Dutch Processing Industries

2.1 Boundaries of the innovation system

The first step of an innovation system analysis is defining the boundaries of the system. Contemporary innovation system studies define various levels of system boundaries along geographical, sectoral, or technological dimensions. Our analysis considers the following boundaries:

- *Geographical boundaries:* The analysis focuses on the Netherlands; but allows for flexible extensions of national contextual boundaries, for example, to include relevant firms linked to the supply chain or relevant EU institutions that affect the innovation system.
- *Sectoral boundaries:* The analysis focuses on the processing industries in the Netherlands. These were initially limited to the energy-intensive sectors like steel, chemicals, and refining; however, the research found relevant linkages within the innovation system to other sectors that include process technologies, such as food.
- *Technological boundaries:* The technological innovations under consideration mainly include digital technologies for energy efficiency; however, the analysis was open to general digital innovation processes that could also affect energy-efficiency-related technologies. A more detailed view of these technologies will be discussed in Section 2.2.

The innovation system around digital technologies differs from typical technological innovation systems in one crucial way. Past studies around innovation systems have focused only on "singular" technologies, such as industrial heat pumps or biomass [1, 2]. While there may be different variants of these innovations (such as different types of heat pumps), the number of variations of digital technologies can be too numerous to capture into a singular technology. This variety, termed *innovation complementarity*, is a core feature of key-enabling technologies like digitalization [3-5].

We do two things to navigate this complementarity in our innovation system analysis. First, it is still important to capture the variety of digital technologies involved, so we define categorizations of digital technologies relevant to understanding the innovation system's dynamics (see overview in Section 2.2). Second, we refrain from drawing strict technological boundaries to the innovation system. Instead, we focus on the actors and networks responsible for the different phases of all digital innovation (see overview in Section 2.3).

2.2 Technological and technical system structures

2.2.1 Technological categories of digital technologies

There are a few main categories of digital technologies that are relevant to the processing industry, particularly for energy efficiency purposes. Drawing on categorizations from a recent industrial report for the Dutch processing industry [6], these are:

1. Asset management analytics: Optimizing assets that are part of processes
2. Energy management analytics: Optimizing energy flows on sites, i.e., balancing energy generation and use or generating setpoints for operators
3. Advanced process control systems: Closed loop optimizing of specific processes related to assets on sites
4. Digital twins: A virtual representation of physical assets and their dynamic behaviors, enabling a host of innovative activity

As discussed (in Section 2.1), within these generalized categories, there are numerous application areas within them. For instance, energy management analytics can be applied to specific rotating equipment like an electric motor, using data generated via electrical signals. This application would be just one manifestation of digital innovation.

2.2.2 Business models around digital technologies

Three aspects of business models around digital technologies are important to highlight to understand the dynamics of the digital innovation system.

First, digital innovation is often accompanied by a change in doing R&D. Digital innovation does not follow a path where suppliers work extensively on creating a complete product before delivering it to customers. Instead, there is a large amount of continuous feedback and experimentation with customers. Applications of digital technologies thus do not follow a linear progression through the Technology Readiness Levels (TRLs), at least on a micro-level. Given a sufficient base of digital capacity within industries, the progression through TRLs occurs more rapidly.

Second, due to a shift towards servitization of innovation, there is a variety of new business models of digital technologies. A manufacturing industry report based in Germany has modelled examples of these new business setups: Machine & process optimization service, Manufacturing as a Service, Data-driven service, and Production scheduling service [7]. Our interviews and secondary data show that a shift towards these business models is occurring within the Dutch processing industries, including the presence of new firms and firm categories that facilitate these setups.

Third, digital technologies, especially around energy-efficiency applications, typically demonstrate increasing returns to scale. This means that for many technology trajectories, the business models demand the deployment of these tools at a sufficient scale for a successful business case.

2.2.3 A categorization of digital technologies based on innovation processes

The research data analysis reveals an additional technological dimension of digital technologies, which cuts across application areas (Section 2.2.1) and business models (Section 2.2.2). As part of digitalization, we see two kinds of digital innovations that emerge – bottom-up innovation and top-down innovation. In short, bottom-up innovation involves digital technologies that emerge by improvisation in a more open-ended innovation process. In contrast, top-down innovation involves digital technologies that emerge through innovation processes with pre-determined technological objectives. The relevance of this dimension will be discussed in more detail in subsequent sections.

2.3 Social and organizational system structures

This section will provide an overview of the actors and networks involved in the digital innovation system of the Dutch processing industries, summarized in Figure 1.

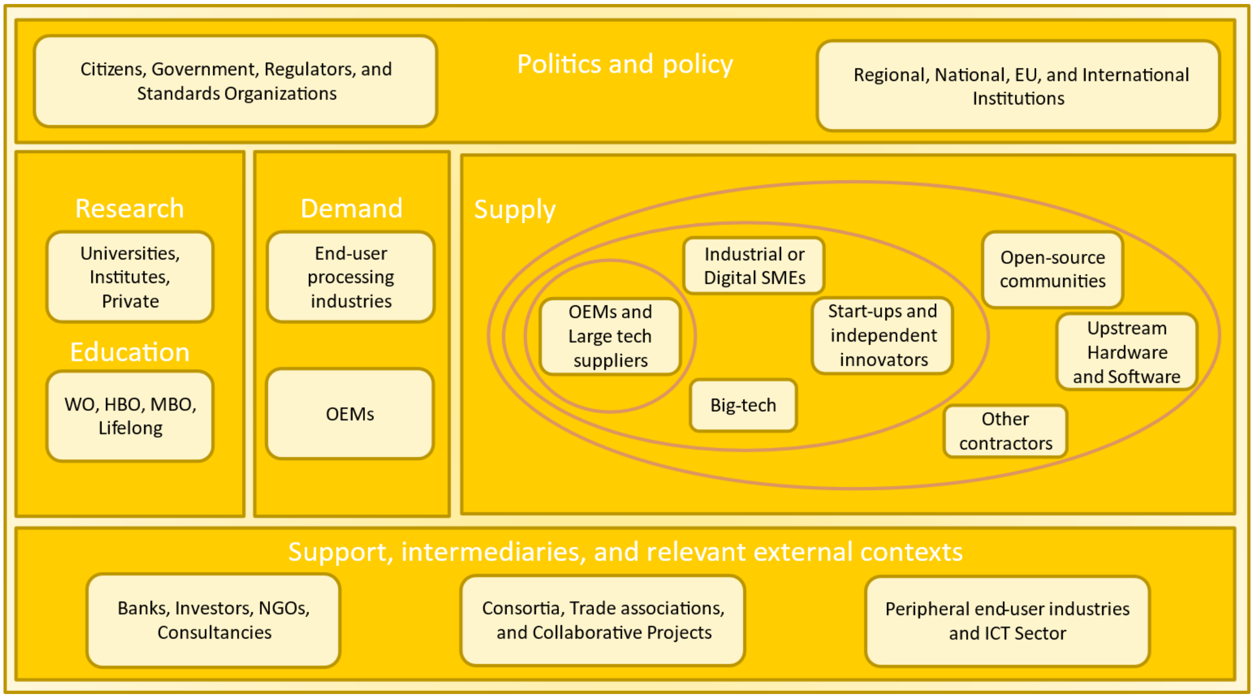

Figure 1: System structure overview - Actor and networks in the digital innovation system of processing industries

The goal of the digital innovation system is to progress digital technologies from their conception to the final demand of the technology. Therefore, the demand side is the main focus of all innovation activity.

End-users in this digital innovation system are the industries in the Netherlands that process raw materials into basic products. These include large, multinational firms such as Tata Steel, Dow Chemicals, Shell, Huntsman, and FrieslandCampina. Smaller end-users, with limited R&D capacity, are also prominent in the Netherlands, such as paper mills and food companies. All end-users vary in their level of centralization. Demand for digital innovation can come from centralized actors within the firm or more localized actors on sites or industrial clusters.

The demand for digital innovation at an equipment level can also come from more prominent Original Equipment Manufacturers (OEMs) for the processing industry. Examples of these firms include Siemens, GE, ABB, and Honeywell. These firms are, however, more often seen on the supply side of the innovation system alongside start-ups or SMEs. In Figure 1, we place OEMs and large suppliers as the first tier of actors on the supply side. The second tier includes big-tech companies, digitally-oriented SMEs, and smaller innovators like start-ups. The third tier includes open-source communities, other independent contractors, and further upstream supply chain actors, which comprises of firms offering analytical expertise, specialized software packages, communication protocols, and hardware. This complex range of supply-side actors is a consequence of the new business model structures around digital innovation (see Section 2.2.2)

Outside of supply and demand, research and educational institutes are crucial parts of most innovation systems, and digital innovation in the process industry also heavily relies on these actors. Relevant national, regional, and global standards (e.g., NEN, ISO) and regulators create the overarching institutional structure for the innovation system.

Several intermediaries play active roles in digital innovation. These include knowledge networks, consortia of industry, and trade associations. They look for system-wide opportunities and aim to stimulate cooperation, open innovation, and advance the agendas of processing industries. Consultancies, both with expertise in digital and industrial activities, are actors that further bridge the digital and industrial world.

Finally, peripheral sectors such as energy, manufacturing, pharmaceuticals, and semiconductors can also contribute as contextual factors to the digital innovation system of processing industries. The core ICT sector also provides essential resources to the innovation system, which include protocols, standards, platforms, algorithms, methodologies, and skills.

3 Diffusion processes of digital innovations in the Dutch processing industries

To identify the activities that contribute to the adoption of digital innovation, thereby linking the supply and demand of technologies, we turn to adoption theory. Rogers defines five stages in the adoption process of innovations [8]. These five stages are – Knowledge / Awareness [R1], Persuasion [R2], Decision [R3], Implementation [R4], Confirmation / Continuation [R5]. To analyze the innovation system defined in this report, this theory needs to be contextualized to fit our empirical case in two ways. Firstly, Roger's theory centres around individual adopting entities. In our case, individual adopters are considered synonymous with individual factories or industrial sites of firms. Secondly, as we analyse the innovation system, we take into account scaling conditions where the individual adoption creates feedback loops for the rest of the innovation system, potentially leading to adoption on different sites or across firms and industries.

The framework described in Figure 2 essentially traces how digital innovations move from conception to the shop floor (i.e., an industrial site). The remainder of this section will describe these five stages and the scaling conditions for the processing industry in detail.

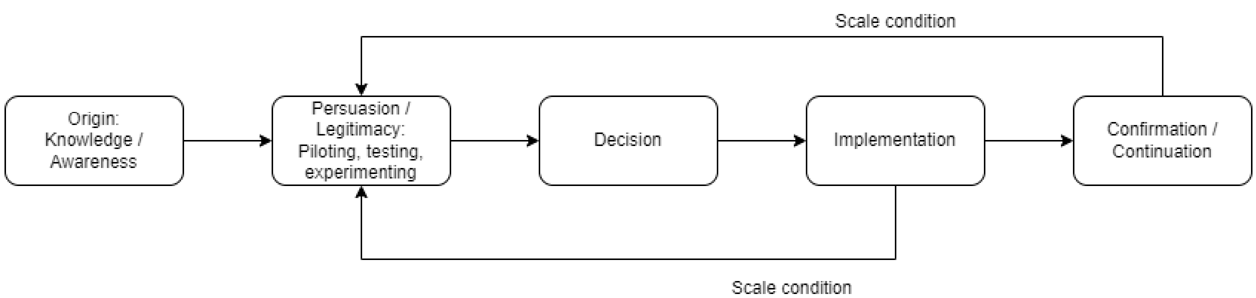

Figure 2: Modified Roger's innovation adoption model

Origin: Knowledge/Awareness [R1]

The first adoption stage is when the end-users are first exposed to the digital innovation. It is essential to discuss the various sources of digital innovation and how the end-users become aware of an innovative technology.

- Internal actors or teams within end-users
  - Different engineering, operations, and business units within end-users expose themselves to new digital innovations through their own internal motivation, which could be targeted towards both short-term, use-case specific goals, or even long-term process, system-related goals. Motivation may also be indirectly driven by external sources like regulation (related to emissions, energy, or safety) or to keep up with competition and advancements in industry 4.0.
  - End-users, particularly the larger international steel and chemical firms, create internal academies and analytics communities to promote innovation within the firm. Firms may use consultancies experienced within the digital space to facilitate the setup of these internal capacities and communities.
  - The end-user provides additional resources to assist bottom-up internal innovation. It includes Enterprise Resource Planning (ERP) systems; collecting and making

accessible data and measurements (data lakes, historians, cloud, etc.); access to tools and platforms to analyze and extract value from these data sources; and security or privacy ensuring technologies and standards.
    - Finally, end-users may also approach and seek out vendors like start-ups, universities, and technology suppliers for specific use-cases or digital innovations they require.
- Start-ups
    - A start-up with an idea or product focused on the process industry may expose its digital innovation to end-users through multiple routes, e.g., bottom-up pitching to operators or local sites; top-down pitching to upper management; or accessing end-users through knowledge networks or consortia. These connections are typically made through geographical or social proximity. For example, start-ups within the Benelux region will exclusively target the Dutch processing industry early on or use their contacts from previous work experiences.
    - Start-ups may also in-directly expose their innovations to end-user via OEMs or technology suppliers who pitch the new digital innovation through their existing products.
- Technology suppliers, OEMs, and other partnered firms
    - There is a shift within technology supplier firms from traditionally supplying only hardware to more services, and digital innovations are a large part of this change in business model. Therefore, in addition to digital innovations coming from start-ups, OEMs and technology suppliers also expose themselves to new digital innovations via their internal research programs (similar to end-users).
    - Digital innovation may emerge from unexpected sources on sites like maintenance contractors who propose digital programs to improve operations and efficiency.
- Knowledge networks, consortia, and learning communities
    - Firm types across the innovation system gain exposure to digital innovation via knowledge networks and consortia.
    - In this case, the modes of exposure are varied and innovation specific. As discussed previously, start-ups may use these networks as a platform to pitch innovations. These networks may identify specific digital innovations of significant strategic importance for the Dutch industries. Innovations with high entry barriers and risks may also be a focus of these networks.
    - Notably, many of these networks may not have an explicit focus on digital innovation. Instead, they often focus on specialized knowledge fields in the process industry, such as rotating equipment, maintenance, safety, etc. Digital innovation then typically emerges as one of the tools for solving field-specific challenges.
    - There are shorter term innovation consortia, running 4-8 years. However, longer term public-private consortia, often termed as “learning communities”, are also crucial sources of innovation. Examples include Chemelot Innovation and Learning Labs (CHILL), Biotech Campus Delft, etc.
- Outside the process industry
    - For digital innovations, exposure within technology suppliers and end-user may come from partners and firms in their supply chain that are beyond the typical process industry firms.

  - These include networking or communication firms, data or cloud infrastructure providers, big tech and platform companies, external data analytics companies, and open-source communities.
  - These firms are exceptionally well-positioned to bring digital innovations into the processing industry that are typically developed or successful in peripheral or unrelated sectors.

Persuasion [R2]

The persuasion stage is the next step in the adoption, where end-users are interested in the innovation and opinions are developed. Forming these opinions demands more legitimacy creation for the innovation.

- The end-users seek out evaluations of the innovation from various sources. They may use internal resources and capabilities (such as their ICT infrastructure, expertise, funding, etc.) to assist these evaluations.
- The actors associated with the origin [R1] of the innovation are typically involved in this phase too by creating pilots, demonstrations, tests, and experimentation to support persuasion.
- When the innovation is at earlier TRLs, this persuasion is typically on the site level, and the operators or managers are only involved locally. During scaling conditions, this persuasion is done on the upper management level, where many more actors must be convinced of the technology.
- Reinvention, changes, and significant learnings for the innovation occur in this stage, typically for the fundamental, technical issues.

Decision [R3]

The decision stage of adoption involves activities that lead to the choice of adoption or rejection of the innovation. Social and organizational structures within end-users play a pivotal role in this stage. As mentioned in Section 2.3, the degree of centralization can determine the decision-making culture. Highly decentralized firms will focus on local solutions, and decision-making is then typically limited to individual site-level actors. Conversely, highly centralized firms will rely on top/upper management to make decisions on adopting digital innovation. This typically involved more actors, including the centralized information technology (IT) teams, strategic business teams, localized operators and managers, system integrators, and knowledge field-specific specialists.

Implementation [R4]

The implementation stage is where the end-user begins to use the digital innovation, which can be done in varying degrees. The end-users with the resources to support digital innovation will use this capacity at this stage. These resources can include an infrastructural commitment to ensure sufficient security, privacy, and technical assistance. Significant activity around system integration occurs here, involving interaction between operational technology and IT teams.

As with the persuasion stage [R2], reinvention, changes, and learnings also occur during the implementation phase. These are typically related to scale, organizational, infrastructural, or social issues. There may be a realization that for the innovation to be successful, more scale is necessary, so there is a reversal back to the persuasion phase to scale the innovation across the site, to different sites, or over the entire organization.

Depending on the organizational structure within end-users, there may be feedback to other local teams via internal knowledge-sharing events. External sharing may also occur via knowledge networks or consortia, as shown in the origin phase [R1]. This sharing is likely to occur only after sufficient time and legitimacy have been created for innovation in previous adoption cycles (i.e., higher TRLs).

Confirmation / continuation [R5]

This stage involves finalizing the decision to adopt and continue using the digital innovation. The confirmation stage is characterized by reflection and re-exploring the persuasion phase [R2]. Throughout the five stages of adoption, a crucial actor or group of individuals typically "champion" the innovation. This technology champion is firmly convinced of the value of the digital innovation and often unknowingly becomes responsible for driving the innovation through the different phases. In this final phase, the continuation of the innovation can also be influenced by the technology champion. This continuation could be an interest to scale up the use of the innovation to different sites or globally, similar to the processes described in previous phases [R4].

Discontinuance is also an outcome of this phase; for instance, if it is discovered during the implementation phase that the resources don't justify the long-term value. However, given the risk-averse nature of the processing industry, these value judgments typically occur much earlier in the adoption phases. While this is the first mention of barriers or failures of digital innovation, it is essential to note that barriers and problems can occur at any point in the adoption phases.

The adoption model in action: Diffusion of an electrical signal analysis tool for motors

To illustrate the adoption model, we go through an example of the diffusion of a digital technology in the processing industry. The example chosen is an asset health tool developed by a start-up capable of predicting rotating equipment failures by analyzing electrical signal data. Three iterations of the adoption model have played out so far over the lifecycle of this single digital tool.

First Iteration:

R1: First, at the early stages of the technology, the founders' initial conceptualization was simply to leverage data science to create value in the processing industry. They first approached end-users within the Netherlands. Together with discussions with sites and managers, they codeveloped the idea for the use case using these early customers.

R2: This co-development allowed them to demonstrate the tool in an experimental industrial environment in addition to a lab setting. Using these early partners, they went through three versions of the tool, each time discovering technical problems and tweaking the product. For example, they found that using electrical data rather than vibration sensors would be a more innovative approach and decided to build their own sensor-based product. They worked together with local, accessible hardware suppliers during this stage.

R3: The fourth version was the most technologically successful and was deployed and implemented by the early partners. However, there were several decision-making points in the previous three versions where it was decided not to continue with the product version. These decisions came mainly from the start-ups during this early product development stage. The end-users involved were aware of the partnership's novelty and developmental nature.

Second Iteration:

R1: With the technology at a well-developed technical stage, the firm looked for more customers in the industry. This was done through conferences and events to build on their networks and further expose their technology to more end users. End-users that had a need for such innovation also began to approach them through this exposure. The firm also used industry consortia to discover key interested end-users and to acquire crucial financial and technological resources to scale up their innovation on sites.

R2, R3: The persuasion phase became more straightforward due to the available demonstrations and data from the previous adoption iteration. European and national subsidized partnerships assisted in demonstrating the value of their technology at scale. This meant that decision-making became easier for end-users as the risk was spread out and borne by multiple partners.

R4, R5: There were crucial learnings during the implementation that went beyond technical aspects. Scaling was discovered to be challenging, and more organizational elements began to become evident. For instance, while adoption took place easily on individual sites, moving to different sites within end users was difficult. There were new learnings about internal operations within the technology from identifying critical socio-technical success factors in profitable partnerships. Failed partnerships were also learned from, feeding into further understanding of their product value and shaping future partnerships.

Third Iteration:

R1: In the current state of affairs around this digital tool, the firm is attempting to scale to larger customers, using the learnings from the previous adoption iterations. In addition, they have struck strategic partnerships with platforms and larger OEMs. These larger suppliers are able to incorporate the tool into their existing services while providing access to a larger pool of end-users.

R2 – R3: The larger firm uses its existing customer base and industrial proximity to create better legitimation and manage the complex decision-making of larger end-users. However, learnings from these new forms of partnerships are expected to emerge over time.

Using the adoption model to trace the diffusion of innovation allowed us to structure the various socio-technical dynamics involved within the industry. It also revealed the first examples of barriers and problems that digital innovations can encounter during their lifecycle. All the barriers identified from the research data are linked to the adoption phases and discussed in detail in Section 4.

4 Barriers to digital innovation diffusion

In Section 3, the report outlined five phases involved in adopting digital innovation and primarily described the drivers of this adoption. However, barriers and systemic problems can be encountered by the innovation at any stage in the adoption model, resulting in the innovation being slowed, stuck, or even rejected. Indeed, our empirical analysis indicates that many innovation processes have not (yet) reached stages 4 or 5. Common and persistent barriers hinder the performance of the innovation system, which may motivate, and focus innovation policies aimed to improve the innovation system performance. In this section, the systemic barriers have been grouped into nine categories and discussed in detail.

Incentive differences across teams and hierarchies [B1]

Interviews strongly suggest that the different incentive structures of teams within end-user firms are a root source for multiple barriers within the innovation system. The different organisational units relevant here are top management, the IT/ICT division, the operators and engineers on the shop floor, and the R&D and labs.

The top management has clear interests in long-term strategic value, partnerships, and sustainability issues. The IT/ICT division is oriented toward supply chain applications, infrastructure, customer relationship management, data security, and privacy issues. The operators and the shop floor are concerned with improving factory operations, workflows, and activities that contextualize information for better decision-making. They are interested in digital innovation involving production, operations, downtime, and use cases that are functional for day-to-day activities. The R&D and technologists are focused on cutting-edge developments in digital technologies, concrete, measurable outcomes, and scalable technologies. Typically, most financial resources for innovation get allocated to the R&D divisions. These teams also perform an essential role across the organization, trying to prevent “reinventing the wheel” type situations. For example, they try to facilitate and provide resources to connect different sites trying to bring about similar digital innovations.

Decision-making challenges for bottom-up digital innovations [B2]

The digital innovations from start-ups and bottom-up sources find substantial barriers during their scaling phases of adoption. While an innovation may be successful at a localized site, moving to other sites (an example of scaling conditions) becomes difficult as the decision-making shifts to upper management. This is particularly the case for end-users with centralized organizational structures. Legitimacy then needs to be created again within upper management i.e., the adoption moves back towards the persuasion phase [R2]. Creating legitimacy and persuasion for upper management is more challenging for digital technologies compared to traditional engineering (first principle) innovations. Upper management wants more concrete solutions that are measurable and scalable. For instance, it can be more difficult to pitch innovations based on machine learning, which improves over time and with access to data. Without sufficient persuasion, vital resources such as time, people, and money may not be made available for the digital innovation.

Overall, stemming from the incentive differences described in the previous barrier [B1] polarized persuasion within the end-users for digital innovation creates barriers at the decision-making stage [R3] particularly during scaling conditions.

Disconnection of cutting-edge innovation with the shop floor [B3]

The cutting-edge innovations that come from top-down innovation do not always align with the needs and incentives of the shop floor. Previously discussed incentive difference [B1] results in the R&D and technology innovation teams in end-users (and also several technology suppliers) being too many steps ahead of the shop floor.

Digital innovations may not work that well in practice, or innovations are just not useful enough for the incentives of the shop floor – the actors who have to implement the innovations. This incentive misalignment can be misrepresented as "resistance to change" by the shop floor.

The top-down innovation processes may not involve the right actors from the shop floor during the persuasion and decision-making stages. During the implementation phases, a lot more effort typically goes into ensuring that the practices are changed for the innovation to succeed. Necessary reinvention and learning can be overlooked when the shop floor is not entirely on board with the innovation.

The interviews revealed some attempts at solutions to this barrier. Transparent methodologies and training are needed for anything beyond plug-and-play solutions or innovations that fit within existing workflows. When significant adjustments to workflows take place, all actors must be made aware. There is also strong evidence that successful digital start-ups in the process industry have taken this onboarding process very seriously.

Concerns of information technology teams and a general fear of algorithms [B4]

The serious concerns in the agenda of IT/ICT teams, such as around reliability, security, and privacy, result in barriers to digital innovation involving operational technologies. The interviews showed several examples, such as delays in getting approval for using digital tools, hesitance to leverage cloud technologies beyond the firm's control, and overestimation of the value of firm data (hindering the use of such data for suppliers). These barriers result in uncertainty during decision-making [R3] and a lack of resource availability during implementation [R4].

These challenges are also strongly linked to an overarching, growing societal concern about algorithms. Given this fear of algorithms and loss of autonomy, the industry expresses the need for secure and transparent algorithms. This is a barrier that directly affects the legitimacy creation [R2] and acceptance of innovation [R5]. Solutions around these challenges are starting to emerge, such as frameworks for human-centred design processes.

Lacking digital infrastructure [B5]

As discussed previously, digitization (enabling digital data creation) serves as necessary groundwork for subsequent digitalization to build on top [R1]. The end-users can vary significantly in their level of digitized assets and infrastructure. While many assets have, over time, become digitized (for instance manufacturing execution systems; lab, maintenance, climate, or compliance data), some firms are behind on this base level of digitization. Further, the digitization of certain assets has also been ignored. The level of digitization can be insufficient, e.g., regarding the timescales of data the digital infrastructure produces. Overall, this can hinder the origin [R1], persuasion [R2], and implementation [R4] stages of adoption.

Additionally, technology suppliers and start-ups often find a lack of sufficient networking infrastructure to deter the innovation's implementation stages. There can be a difference between the sites of an end-user firm in terms of the quality of hardware and networking infrastructure like IoT devices, Ethernet, and 4/5G. Communication protocols such as Fieldbus communication standards can also be lacking.

The interviews show that a solution to these barriers involves the standardization of infrastructure. This can emerge within large end-user firms, or industry-wide through collaboration. An example includes the recent work around “reference architectures” and “ontologies” across the Dutch top sector. As discussed previously, standardization of data within firms is vital in the origin phase [R1], but interviewees acknowledge that some sites are behind others. However, they also point out that there needs to be a balance between standardization and flexibility toward the needs of the local site. Managing this balance is often a challenging task for some firms. As demonstrated in the example (Section 3), some suppliers even try to overcome this barrier by choosing to produce the data themselves, via their own sensors and equipment. They then rely less on the quality and quantity of data within end-users. Finally, new infrastructural technologies are up and coming, which has the potential to increase connectivity and the volume and variety of data. Examples include edge computing and mobile sensors.

Job rotation and the loss of innovation champions [B6]

The role of innovation “champions” has been discussed previously [R5], i.e., actors who are highly influential in the persuasion and implantation stages. However, the organizational culture at multinational end-users often tends to favour periodic job rotations (e.g., across sites or to different teams and business units). While this rotation facilitates the scaling conditions of certain innovations, they might, conversely, create barriers to other digital innovations. If a champion has moved away from the project or team, there is usually a slowdown (or even a reversal) in the adoption process as there is a loss of attention for the innovation. The interviewees identified potential solutions for these barriers, such as road mapping, lifecycle management, organizational culture awareness, and change.

Skills-related challenges [B7]

The interviews have identified two kinds of skill-related challenges for digital innovations. The first kind is skills related to the shop floor. This includes practical skills by employees on work floor to implement digital technologies. There is also an acknowledgement of a special kind of new actors, call “data translators”, who work to bridge digital knowledge with domain (i.e. process technology) knowledge. These skill barriers are linked to the implementation phase of adoption [R4].

The second kind of skills is on the managerial level. The managers are given significant responsibilities, including assessing and identifying a suitable variety of digital tools for their organizational unit. The pace of evolution of digital technologies is unprecedented, compared to typical innovation cycles in the processing industry. For example, the industry norm in blockchain technologies has shifted rapidly from proof-of-work to proof-of-stake consensus mechanism. Adding to this dynamic factors, there is also a tenancy within technology suppliers in the digital space to over-promise and underdeliver in an increasingly competitive digital race. The skills managers need are linked to their ability to process information during the persuasion phase of adoption [R2].

Skills, overall, have received quite some attention from knowledge networks like consortia and trade associations who are attempting so to address these challenges. Example of this is the EDISON Data Science Framework [9], and the digital skills framework in development, focusing on workers, managers, and academic. The solutions, besides lifelong training, include keeping track of new developments and validations, coupling sectors together to increase learning between success cases, etc.

Scale-related challenges [B8]

A characteristic of several digital innovations is that they are systemic and require scale for their business models to be viable (Section 2.2.2). We observe several dynamics that link to this scale intensity.

Due to differences in the digital advancement of end-users [B5] and the decision-making challenges described [B2][B4] SMEs and technology suppliers are targeting specific end-users who have the capacity to implement their innovations at scale. Further, suppliers are incentivized to focus on innovations that do not require many changes from the end-users, citing that persuasion [R2] works better when radical change is not demanded in workflows and assets.

Path dependency and lock-in processes are also occurring within the Dutch processing industries' digital innovation system. Existing technology suppliers with long-standing partnerships and assets at end-users are being structurally favored by end-users. Further, 'Big Tech' and other large platform services have the organizational capabilities to navigate the complex decision-making cultures of end-users to push their standardized products in a top-down manner. The apprehension towards "vendor lock-in" is a growing concern in the industry. Interviews have shown examples where top-down pressure has disrupted the tools and workflows that the shop floor traditionally uses.

Overall, these scale-related challenges are decreasing the variety in the origin phase of adoption [R1]. Technologically more optimal or socially more accepted innovations (for the shop floor) may discontinue [R5] due to these scaling conditions.

Partnership-related challenges [B9]

There are challenges related to building partnerships within the industry that hinders the digital innovation system. These challenges are seen to occur at the knowledge networks and consortia levels. While such intermediaries play a crucial role in digital innovation (see Section 2.3), participants may be hesitant to commit enough resources, and non-disclosure agreements may affect knowledge sharing. Personnel change often occurs at differing rates in different firm types; for example, university researchers have longer contracts than industrial or project actors. This results in slow progress in digital innovation (similar to [B6]). Further, there is sizeable organizational proximity between some firms in these networks – such as between a large multinational processing firm and a small digital start-up – which can deter the agile culture that surrounds certain digital innovation processes.

These challenges also occur outside consortia, as start-ups find it challenging to partner with large end-users bilaterally. The pace of adoption is misaligned, and end-users can lack the absorptive capacities and supportive resources necessary to work with start-ups during the persuasion [R2] and implementation [R4] phases. Smaller firms are occasionally forced to seek partnerships with large technology supplier partners to satisfy the scaling conditions.

5 Conclusions

The processing industry in the Netherlands seems to be at the beginning of a rapid digital transformation that will bring about both incremental and radical change to different aspects of the industry. A range of actors, firms, networks, and institutions engage in numerous activities contributing to the development and diffusion of digital innovation. This report provides a broad socio-technical overview of this digital innovation system. The key actor groups on supply, demand, intermediation and policy have been identified and their relations have been analysed. Notably, the nature of digital innovation, the surrounding new business models, and the emergence of new types of firms have resulted in a complex supply side.

The study presents a five-stage adoption model, describing how digital innovation emerges, develops, and finally reaches the shop floor of the processing industry. This structured approach to understanding the diffusion of innovation can be particularly insightful for practitioners and policy-makers. Identifying the stage of the innovation and the challenges that could emerge in the different stages can allow for more informed planning and execution. Further, the study identifies nine overarching socio-technical barriers to digital innovation. These include (1) Incentive differences across teams and hierarchies, (2) Decision-making challenges for bottom-up digital innovations, (3) Disconnection of cutting-edge innovation with the shop floor, (4) Concerns of information technology teams and a general fear of algorithms, (5) Lacking digital infrastructure, (6) Job rotation and the loss of innovation champions, (7) Skills-related challenges, (8) Scale-related challenges, and (9) Partnership-related challenges.

Two systemic root causes of these barriers are essential to highlight. First, the misalignment of incentives of different teams within the industry feeds into several barriers – including the challenges of decision-making, acceptance, disconnection with the needs of sites, and other frictions between upper management and the shop floor. Second, the practices and activities necessary for successful digital innovation differ in crucial ways from traditional innovation trajectories for the processing industry. Fundamental differences include the pace of evolution of digital technologies, the non-linear technology development curve, the variety of use cases, and the interrelations and dependencies between digital technologies or infrastructure. For example, innovation practices such as agile working, minimum viable products, and continuous feedback might contradict the current functioning of the industry. Policy makers may have to depart from or adapt TRLs and other dominant innovation indicators to account for these differences.

Finally, this study's interviewees also identified potential isolated solutions that could help mitigate some barriers to digital innovation. However, for systemic problems, a comprehensive and systemic perspective on these ways forward is also necessary. Further research is needed to systemically identify and assess the policy directions required to improve the performance of the whole digital innovation system of the Dutch processing industries.

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Appendix: Interview data

Interviewees	Firm Type	Role	Length (mins)	Date
1	Consortia	Business developer	120	15/05/2022
2	Consortia	Industry 4.0 Program Managers	63	23/06/2022
1	Consortia and consultancy	Self-employed	55	11/08/2022
1	Consortium / Consultancy	Managing director	54	08/09/2022
1	End-user Chemical Industry	Analytics and Asset health Manager	94	26/08/2022
1	End-user Chemical Industry	Technology associate	58	22/09/2022
2	End-user Energy and Chemical Industry	Engineer / Commercial Analyst	77	25/08/2022
1	End-user Energy and Chemical Industry	General manager	53	25/10/2022
1	End-user Food and Chemical Processing	Research and Development	58	13/09/2022
1	End-user Food and Chemical Processing	Technology and Business Development	50	21/09/2022
1	End-user Food Processing	Research and Development	54	13/09/2022
1	End-user Food Processing	Operations manager	49	22/09/2022
1	Industrial-Digital SME	Founder	84	22/03/2022
1	Industrial-Digital SME	Installation / Product development	90	22/06/2022
1	Industrial-Digital SME	Internal Operations	90	24/06/2022
1	Industrial-Digital SME	Business intelligence consultant	50	29/08/2022
1	Industrial-Digital SME	Founder and Business Development	54	01/09/2022
1	Large Technology Supplier	CEO	53	02/09/2022
1	Start-up	Founder	54	22/07/2022
1	Start-up	Founder and CEO	54	31/08/2022
1	Start-up	Founder	68	12/09/2022
1	University	Researcher - Social Sciences	55	31/08/2022