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I AM RRI

Webs of Innovation and Value Chains of Additive Manufacturing under Consideration of RRI

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D5.3 STRATEGIC RECOMMENDATIONS

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ON RRI OPENINGS IN THE WIVC IN AM (IAMRRI_D5.3_V1)

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Abstract: This deliverable draws lessons and provide strategic recommendations based on the findings of the research work that has been conducted in IAMRRI. Particularly, the recommendations are based on the openings identified by analysing the results of IAMRRI research activities, focusing on identifying the best options to implement RRI within additive manufacturing (AM) webs of innovation value chains (WIVC).

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List of Abbreviations

ABM&S	Agent-Based Modelling & Simulation
AM	Additive Manufacturing
IVC	Innovation Value Chain
NGO	Non-Governmental Organisation
OEM	Original Equipment Manufacturer
RRI	Responsible Research and Innovation
SME	Small-Medium Enterprise
WIVC	Web of Innovation Value Chains
WP	Work Package

1. INTRODUCTION

1.1. Aim of the Deliverable

The aim of this deliverable is to draw lessons and provide strategic recommendations based on the findings of the research work that has been conducted in IAMRRI. Particularly, the recommendations are based on the openings identified by analysing the results of IAMRRI research activities, focusing on identifying the best options to implement RRI within additive manufacturing (AM) webs of innovation value chains (WIVC).

Therefore, the results that we have considered in this work derive from:

- the conceptual analysis of the behaviour of RRI within the additive manufacturing webs of innovation value chains (WIVC).
- the findings of several use cases conducted within the project.
- from the modelling exercise and the outcomes of the simulations carried out in IAMRRI.
- and from the IAMRRI foresight process.

1.2. Target Group and Purpose of the Strategic Recommendations

The description of the openings and the recommendations included in this report are targeted primarily to decision makers in organisations that fund or perform research activities related to the AM technologies and AM webs of innovation value chains (WIVC). In addition, other stakeholders of such WIVC such as industrial organisations, clusters and regulatory or standardisation bodies will find information on how to implement RRI within AM WIVC. Learning of the IAMRRI project might be used to understand other upcoming new technology fields, if they have similarities to AM. First, the learnings derived from different research activities and approaches towards AM WIVC. The relationship with RRI is presented. These general lessons provide an overview on the conclusions and on the barriers and drivers identified in the different research stages of IAMRRI. Second, based on these learnings, openings for RRI within AM WIVC are described and recommendations on how to address these openings are provided. The goal is to offer specific and strategic recommendations to sustain and promote the spread of RRI practices through the AM innovation system and networks.

2. IAMRRI APPROACH TO RRI AND RRI OPENINGS

RRI under the scope of H2020 RRI is described in the following way: *"Responsible research and innovation are an approach that anticipates and assesses potential implications and societal expectations with regard to research and innovation, with the aim to foster the design of inclusive and sustainable research and innovation."*[1]

[1] https://ec.europa.eu/programmes/horizon2020/en/h2020-section/responsible-research-innovation

The understanding of RRI within the IAMRRI project is based on the so-called RRI keys, that is, Ethics, Gender Equality, Open Access, Public Engagement and Science Education. They are also referred as political agenda of European society. A brief definition of each key is offered below:

- Ethics is an integral part of research for all activities funded by the European Union, and its compliance is seen as pivotal to achieve research excellence. It includes research integrity, ethical reflection, and ethical regulation, explicitly highlighting the involvement of children, patients, vulnerable populations; the use of human embryonic stem cells; privacy and data protection issues; and research on animals and non-human primates.

- Gender equality is defined as a value of the EU and addressed by the European Commission in research and innovation activities in three dimensions: ensuring gender balance in decision making, addressing gender balance in research teams and integrating the gender dimension in the content of R&I activities.

- Open access refers to the practice of making research findings and scientific information rather freely accessible to the scientific community and to any other interested party.

- Public engagement refers to co-creating the future with societal stakeholders, including civil society organisations or, more broadly, citizens.

- Science education on a wide societal basis enables the increase in the knowledge of society, so that citizens acquire knowledge about science to participate in the dialogue between science and society.

RRI openings are considered within the IAMRRI project as openings are places within the WIVC where RRI can be implemented. The openings offer opportunities to implement RRI at the level of the AM WIVC and at innovation value chain level, in the different stages and gates of the innovation process.

3. LEARNINGS FROM IAMRRI RESEARCH ACTIVITIES

3.1. Learnings from the Analysis of RRI within AM WIVC

Webs of innovation value chains are complex and there is no universal explanation of success factors that would explain performance. The literature study of project level economic performance and strategic impact (Van de Kaa et. al., 2019, chapter 4) revealed that there are multiple different types of AM projects: AM development projects, AM implementation projects, and new product or new service development projects. Each specific project in the different levels of the value chains has its specific factors that promote performance. As each project involves its specific actor-networks, there is also a need to consider from whose perspective performance is viewed. The complexity of the innovation system in AM implies that in each of the project types there is a unique constellation of performance-enhancing factors and network of actors, and each of these project types requires dedicated research.

The development of AM as a technological innovation has progressed relatively slowly during the past decades. AM was invented already almost four decades ago, but only the development during the past ten years has provided a stable and good enough technology to really start to produce end usable parts. This behaviour is often described a disruptive innovation. The beginning of such technology can be dated to the invention of the concept of building up an object layer-by-layer. Basic research in mechanics and materials has been the breeding ground for the development of the new manufacturing technology. As illustrated by our retrospective cases, what we can now consider to be a market-ready AM machine has required many basic research projects before the possibility to conduct applied research to find out applications useful for commercialization. We anticipate that this development will accelerate now that the core technologies begin to mature. The focus is likely to move from mere technology development to the development of AM applications that can be commercialized and their respective AM innovation value chains. Also, this development will require investments from both the public (EU-level) sector and from the companies.

Additive manufacturing is an umbrella term for different technologies all based on the layer-by-layer (additive) production principle. The diversity of technological alternatives for AM will require justified choices of focus in commercialized AM technology solutions: which could prove to be the most viable technology options with the most credible commercial potential. Several families of AM technologies can be used for polymers, metals, and ceramics. These technologies are not restricted to one material only and, in fact, the majority of the technological solutions used for, e.g., ceramics materials are derived from solutions developed initially for polymers. As different AM technologies can be transferred from one AM material to another to some extent, there is a need to promote and support knowledge transfer between the alternative technologies, to speed up the potential for commercially credible solutions.

Moreover, AM has possibilities and benefits in many different fields. The diversity of applicable fields or sectors requires choices where to focus on the domain of applications: which could prove to be the most viable application options achieving the best possible value from AM technologies. Depending on the application industry, the benefits of AM can and need to be maximised. AM will not be a technology to substitute conventional manufacturing. The future will show if AM is found in consumer end applications like in medical use, or in B2B high-tech fields where AM can add value in enabling very unique, high-end, and complex applications. Advanced and tailored solutions are needed in versatile application domains, ranging from space technology (such as satellites) to highly functional medical implants. There is still research need to find out the industries and applications where this new technology can add the most value.

To understand the technological and application development of AM, there is a need to grasp the nature of AM as a systemic innovation (Martinsuo & Luomaranta, 2018). Successful innovation does not only take place in one isolated sector, but complementing innovations are needed within the complex networks of AM. For example, IAMRRI project has revealed the necessity for simultaneity and sufficient connections between AM-related designs, software development, material development, availability of technology, application development and digitalisation (Martinsuo et.al, 2020). Additive manufacturing relies on 3D designs of the products and AM added value requires acknowledging the AM manufacturability requirements already in the design phase. Earlier, the lack of good 3D design software and related hardware was the bottleneck for the usability of AM, but as the 3D design software and information system capacity are sufficient, there is the possibility to start using AM in more demanding applications, such as creating a bespoke implant design directly from patient-specific imaging conducted in the hospital.

The systemic features of AM innovations are clearly visible in the webs of innovation value chains. The criss-crossing of value chains is both the requirement for and result of development occurring at any location of the value chains. The criss-crossing in the webs of innovation value chains requires coordination between different organizations involved and timely implementation of development actions.

When analysing the behaviour of RRI within AM webs of innovation value chains (Martinsuo et. al., 2020) we see that all RRI keys are highly interrelated and interdependent, and that any strategic action to strengthen one key in the AM WIVC may have an impact on the others as well. The RRI key ethics is the one that has a bigger effect on the AM innovation system. Ethical considerations are very important for technologies in an early stage to reach societally needed innovation. Similarly, when expanded, science education can bring about tremendous benefits for the development of the innovation, because it enables having a highly qualified workforce.

Open access is a strong driver for innovation in the AM webs of innovation value chains, being a highly active key and not very dependant from the other RRI keys. It has a direct influence on science education, interpreted by the option of students and teachers to get low-barrier access to the up to date research.

RRI's effect on the AM innovation value chain is higher at the early stages of the innovation process, it is at the research and idea generation phase where there is more freedom in decision making and the challenge and barrier for integrating RRI considerations is rather low. Funding organisations can drive RRI orientation by asking for open access, gender equality, including education or assessments on societal impact. When the innovation gets into development phase the option for introducing RRI is remarkably lower, when not included in the idea generation phase. It is further decreasing on the diffusion phase. In addition, the gate that opens between the idea generation and the idea development phase offers the highest possibilities for introducing RRI when not done before by setting RRI criteria or standards as gate keepers. Standardisation as bottom up community approach or legislative regulation might strengthen the gates for implementation of RRI.

As mentioned before, AM WIVC are complex systems where many different actors with diverse competences are involved. Some of them, such as research organisations, universities, or AM technology firms and material suppliers, have a direct influence on the innovation process. Others such as government, funding organisations, and standardisation organisations build the environment for the AM webs of innovation value chain and set the framework. The different roles that actors take within the AM innovation network leads to different potential of RRI keys with respect to pushing towards a social oriented innovation. Universities and research organisations are most affected by RRI keys and can trigger the introduction of measure for implementing RRI keys, thus influencing the whole WIVC. In the case of firms, the keys gender equality and public engagement are the ones having the strongest effect on them. Additionally, policy makers have the most intensive relation to all the RRI keys and can promote RRI and influence others by their actions (Martinsuo et.al, 2020).

3.2. Learnings from IAMRRI Use Cases

During IAMRRI different use cases were conducted. On the one hand, retrospective innovation use cases were analysed within the development of the IAMRRI SKIN model. The aim was firstly to understand the innovation value chains within the AM industry. More specifically, the identification of a number of typical likely actors in various stages of the innovation value chain was in focus. In addition to that the identification of secondary stakeholders that do not take directly part in the innovation value chains of AM products or services was a goal. The study of the interactions of all actors in guiding the innovations toward desirable performance outcomes was very essential. The retrospective use cases were also aiming to understand the kind of capabilities and skills these actors have (i.e. the KENEs[2]) for the SKIN agent base modelling and what kind of other mechanisms like incentives, requirements through standards, patents and regulations or market mechanisms influence the WIVC.

On the other hand, as planned in WP4 of IAMRRI, two specific use cases were carried out, one regarding the medical sector and the other one related to the automotive sector. The objectives of these cases were to provide strong empirical investigation on the RRI openings and to assess the reliability and the applicability of the simulation model developed within the project. Participant observation (Malinowski and Kuper, 2014/1922; Atkinson and Hammersley, 1994) was the main methodology used to investigate the case studies. This allowed to get a deep understanding of the innovation participants and processes, as well as a more specific understanding of the innovation processes and actors of each use case (Sischarenco et. all, 2021b).

3.2.1. IAMRRI Retrospective Cases

During the early days of AM development basic research in mechanics and materials were driving the development. Now also the first real AM applications have emerged (i.e., products that benefit or are solely manufactured with AM technology). This has induced another change: AM applications now become the driving force for AM development which creates and opens new possibilities for basic research in technologies, too. For example, regarding metal alloys, now thanks to AM processes there has been a finding in hindsight about metal alloy's microstructure that was not known before.

Additive manufacturing is not yet a mature technology to be used in supply chain of goods but consisting of many different elements at the level of operations as well as with innovations. To develop innovations both in product and AM technology, there are five types of innovations topics[3] . We identified (not in particular or hierarchical order): AM material research, AM technologies, AM services and business models, software and digitalization for AM, and the AM manufactured products for end users (Martinsuo, 2020). It was seen that innovations have been taking place on each of these topics.
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IAMRRI research has mapped the different actors involved in the AM innovation value chains (IVCs). As already describe in chapter 3.1 their networks and inter-organizational knowledge transfer are crucial, for AM innovations to succeed in the complex innovation system. Many kinds of organizations are active in the additive manufacturing industry. Research in universities and other research institutions takes place on all the mentioned five levels. The heterogeneity of topics, cooperation forms and diverse innovation challenges were observed and were interpreted as a motor for innovation.

[2] Artificial wording for "knowledge" and "gene" of an actor, typical to characterise the knowledge capital of actors in the SKIN agent base modelling

[3] Main innovation topics were named level in D2.4

Similarly, research and innovation take place in industrial companies that either develop new materials, new kinds of machines, new kinds of software, new kinds of products, or new kinds of business models to create business from additive manufacturing. Both universities and companies transfer knowledge of additive manufacturing either through the education system or through industrial cooperation, and little by little the new technology is being adopted widely in the industry.

If viewed retrospectively and through the main innovation phases only (idea generation, product development, diffusion), individual AM innovation value chains might be seen as a rather linear processes, but there are many feedback loops caused by the strong interrelations of the various levels within each phase creating a complex nonlinear innovation pattern. Different organizations have their different powers to influence and drive the innovation system. The retrospective cases in IAMRRI project revealed that these apparently independent innovation cases are not necessarily independent at all, but they are interrelated (Martinsuo et. al, 2020; Sischarenco et.al., 2021a, 2021b). For example, additive manufacturing machine innovation started a new material development, so the idea for a new machine actually was a driver also for the idea of new material.

The main learning from retrospective cases is that there are several possibilities within the webs of IVCs to contribute to the responsibility in innovations. Certain organizations operate in many different innovation value chains and levels, which would enhance the spreading of RRI, if that organization chooses to use the principles of RRI and be explicit about it. Innovations can take a lot of time before diffusing to society, though. It could be potentially important to identify the optimal innovation episodes where RRI principles are likely to become shared across different organizations and, therefore, could be the most impactful.

3.2.2. AM RRI Use Cases

IAMRRI use cases were executed purposively in two different industries: medical and automotive. These industries differ in terms of the production volumes, the financial power of the involved partners and the application use of AM. In the medical industry, AM product innovations are created in unique and complex solutions (i.e., patient-specific implants that provide better biocompatibility and higher functionality and create value for humans compared to traditional implants). It is likely that the medical sector will benefit from the option of mass-customization of applications by AM applications, i.e., using AM for bespoke products whose basic designs are fixed but certain parameters are fully adjusted based on an individual user. In automotive industry, the first AM applications are in high-end and performance-enhancing components and tools used to mass-produce traditional parts. In automotive industry, the possibility of using AM in mass-production might be a future target.

The differences between medical and automotive segments use cases are reflected in the required effort of 3D design and AM manufacturability planning. In each patient-specific implant, there is a need to design each manufactured implant separately, whereas in automotive sector each design is expected to be replicated in AM manufacturing (at least in small batch production). Therefore, the cost of design is divided differently into products in these industries. Mass-customization in the medical sector could imply the need to standardize the design of medical implants so that the customizing and manufacturability planning of implants can be streamlined, whether it is done manually with design parameters or with artificial intelligence aided design. The need for material research and verification is somewhat similar in both industries, although in medical sector there are additional demands due to the certification requirements.

In both use cases, pre-competitive phase of new emerging industry allowed companies to cooperate more freely. In established and mature industries where the logic is to capture as big a market size as possible and secure competitive advantages, the openness of cooperation does not flourish that easily. Cooperation, however, requires trust between the different organizations, and this was a crucial feature in the use cases. The project partners seemed to collaborate in a way where they could benefit from each other's competences. Trustful relationships allowed the partners to rethink the whole product, complexities of the design from multiple points of views and the manufacturing and testing of the materials. Collaboration is key to successfully navigate the inherent AM complexity. In this trust building phase RRI can be a topic which is discovered by all the partners and individual implementation paths for their cooperation can be drafted.

Companies already have some routines or protocols which can be enhanced with RRI. During the use cases we concluded that there are already some procedures within the companies that could be synergically harnessed with the RRI concept. These are, for example, internal codes of conduct or ethical guidelines of companies. As a self-regulating mechanism, developing routine procedures can be seen as bottom-up process where companies can themselves influence how RRI could be implemented. This of course might require some guidance from the outside and benefit from organizations getting involved in industry-level standardization. Exploiting the existing routines or protocols in organizations would prevent straining companies with excessive external requirements, and this way could also prevent the resistance of change. Companies' understanding on ethics includes sustainability concerns, particularly the use of resources and energy and recyclability security issues and workers' health is another relevant ethic's aspect for companies, particularly when dealing with AM materials in the innovation and production processes.

During the use cases, company partners expressed that publicly funded research projects give them possibilities to interact with universities and benefit from their capabilities, and such cooperation might be harder to establish without such support. In this way, the knowledge and infrastructures of universities can contribute to the AM innovation value chains. Universities and research organisations also have RRI principles already quite well in place (as was noticed), so if not directly transferable to the companies, at least during the cooperation the RRI principles can be taken into consideration. However, it is also noted that in business-to-business relationships RRI inclinations do not play that big role and could be assumed that in these relationships the RRI inclinations are not transferred unless the other party has exceptionally high RRI inclinations or there is an internal or external regulation or standard setting some RRI rules.

Science education was mentioned as one of the keys that could be enhanced in their activities. Partner companies consider science education as a way of balancing their shortfalls in public engagement activities and somehow reaching a wider audience. In addition, they consider it as a way of harvesting for future employees and customers. In their view, the more they engage in teaching and lecturing at university level, the more skilled co-worker and employees they would have available in the future. The relation between universities, research organisations and other organisations would favour this science education orientation of companies, helping them participating in sharing their knowledge without needing to organise specific activities themselves.

Open access is seen as a difficult key to be implemented by private companies. Their need to protect their knowledge outside the network and keep their competitive advantages derives in their reluctancy to provide open access to their data or knowledge. These companies see open access as possibility to disseminate knowledge and information that is not essential for their competitiveness and a way to advertise their added value to potential customers or partners within their networks. However, the possibilities that open access offers it is important for companies, as it provides access to information and knowledge from other potential partners and competitors, fostering the creation of new networks within the AM WIVC.

3.3. Learnings from Modelling Process and Outcomes

The key idea of the IAMRRI project is to build a model that can describe the dynamic interactions in the webs of IVCs for additive manufacturing, including the interaction related to RRI, using agent-based modelling (ABM) simulation. The development of the model itself took place over three stages, all of which required extensive data collection from fieldwork, case studies and statistical data from multiple levels of observation and analysis. The first phase was 1) an extensive literature review and associated synthesis which 2) provided information that was used as a foundation for designing a conceptual network model of AM innovation chains and their associated processes (second phase). During the final stage 3) the model was implemented and adapted so that it could be used to answer the specific questions which the IAMRRI project aimed to answer (gaming experiments). In this section, we provide lessons learned from phase 2 (model development) and phase 3 (model adaptation and simulation).

3.3.1. Lessons Learned from the Model Design

The research question for the design phase is "How can webs of innovation value chains and RRI be most accurately described through an agent-based model?". To answer this question, we build on conceptual framework provided in WP2 and theories of innovation networks, RRI, and SKIN agent-based model. The choice of the SKIN model as a base for the IAMRRI model was founded on a review of 1864 publications, more information can be found in D3.1. Key lessons learned from the designing process are:

First, the proposed IAMRRI model incorporates more complexity than SKIN by the way the innovation process is modelled. It covers the stages of idea generation, development, and implementation, corresponding to the concepts established in the IAMRRI project and our simulation review. The extended model permits generating ideas where not all the capabilities and abilities are readily defined, allowing agents to develop innovation hypotheses over extended periods of time and in cooperation with other agents, not all of whom necessarily profit directly from the sale of the innovation. These idea generation/development and diffusion processes constitute the separate innovation value chains. The model allows for criss-crossings between different IVCs resulting in the development of webs of IVCs.

Second, additional attention is paid to timing in the IAMRRI SKIN model. Unlike in the original SKIN model, innovation and market-related processes may unfold over several time units ("ticks" units of time or iteration steps, in modelling and software development terms). This makes it possible to simulate processes of various durations and use time-related variables in addition to price-related and other mechanisms regulating agents' decision making.

Third, in line with the empirical observations in the AM industry, learning mechanisms are extended so that the agents can learn from each other in more ways (compared to the original model) in the processes of idea generation and development.

Fourth, the RRI policy agendas, also called policy keys (open access, gender equality, public engagement, ethics, and science education) are introduced, mainly through parameters influencing decision-making processes. These RRI policy keys play an important role in allowing the model to address the research objectives of the IAMRRI project.

Finally, some extensions are introduced to adapt the model to the automotive and medical cases. New classes of agents are added, model initialization parameters are adjusted, probabilistic functions are altered, and additional performance indicators are added.

It is important to keep in mind that the model is designed in such a way that it can be adapted to examine other phenomena in the future. For example, we can look at the dynamics of how solutions to novel manufacturing problems are developed. We can also examine how change in regulations or sanction might impact industry structure. And we can re-adapt the model for studying Key Enabling Technologies and how they address societal challenges which can help create advanced and sustainable economies.

3.3.2. Lessons learned from the Model Simulation Results

Innovation is a complex and non-linear process which success depends on the collaboration of varieties of actors. For this reason, ABM was chosen as the methodological approach in the IAMRRI project because ABM can model a heterogeneous population of actors who interact with each other and with the environment in a complex system with unpredictable results. Additive manufacturing is an emerging technology used in a fast-changing environment involving complex interactions among a multitude of actors. Thus, the advantages offered by ABM make this method well suited to modelling the additive manufacturing ecosystem.

The IAMRRI SKIN model includes key features of both RRI and of innovation systems. Diversity, which is one of the main characteristics of innovation systems, is the main driver of innovation process. In the model, diversity among agents regarding knowledge bases and RRI inclination was introduced from the beginning. Additionally, RRI has been considered in modelling IAMRRI SKIN in different ways: First, agents in the model (big and small firms at different stages of the value chain, suppliers, designers, universities and research centres, customers) are endowed with (RRI) inclinations, particularly with respect to open access publication, ethical thinking, public engagement, and gender equality. These inclinations change over time according to their relationships, their interactions, the nature of learning process they are involved in. Second, collaborative networks and innovation value chains must cope with RRI requirements asked by some central organizations, such as Standard Organizations, Regulatory bodies, and Funding Organizations. These are set as thresholds (gates). These requirements act as incentives for agents to invest in RRI practices and in interacting with other agents that show higher levels of RRI inclinations. Third, in the last developments of the model, NGOs, representing the Civil Society, have been included in the modelling of the innovation systems. They cooperate with other agents in developing the innovation ideas and innovation products, guaranteeing the public engagement of webs of innovation value chains.

Using the IAMRRI SKIN model different simulation experiments have been carried out, firstly to verify and validate the model and to ascertain its rigor and valence, and secondly, to understand and identify openings to strengthen RRI in the AM WIVC.

Experiment 1 - Role of Regulatory Bodies

The objective of the first experiment was to observe the role of regulatory bodies in spreading RRI ethical values and to assess the intervention of regulators in the AM WIVC. Therefore, more stringent regulations on the ethical thinking variable were simulated and observed the diffusion of the remaining RRI keys and the impact on the number of agents participating into the networks.

The results show that by regulating on the ethical thinking of companies the implementation of other RRI practices was also encouraged. The results also show that if regulation is too strict, they limit the heterogeneity, the inclusiveness, and the number of collaborative networks. However, low levels of regulation are not good either in determining the evolution of effective networks.

Experiment 2 - RRI Values

The second experiment aimed at investigating if greater relevance was given to the RRI values when selecting the partners of the networks was related to an increase in the heterogeneity of the actors involved in the networks.

The results of the simulations showed that an increase in the weight of the RRI values in the selection of partners corresponds an increase in the heterogeneity of the networks. Therefore, an increase in the diffusion and in the relevance given to RRI practices leads to an increase in the heterogeneity of IVC.

Experiment 3- RRI Cost

The aim of this experiment was to test the model from the economic performance point of view and the variable chosen to do so was the “RRI cost” input variable, as it is related to the costs that are necessary to support responsible research and innovation.

The results point out that an increase of the RRI costs correspond to an increase of the capital invested in the innovations projects and, in parallel, to a reduction on the number of agents involved in the IVC. Therefore, it is shown that investing in RRI is costly for the innovating agents and can reduce the number and diversity of actors participating in the networks and the stability of innovation networks.

Gaming Experiment - Early-stage AM Innovation System

This experiment simulates an early-stage technology development phase of the AM innovation system. This system is characterized by a high number of research institutions and SME company partners. The OEM which will use the technology for producing new generation of AM produced products are hardly active in the AM system. Funding programs are not so prominent at the early beginning, because the potential of AM was not realized in the very beginning. Based on this premises, the objective of the experiment is to understand how the development path of such an early technology innovation system will be, depending on higher of lower funding levels and considering the influence of large firms.

In a first simulation run where the RRI costs are high, there is no funding and large companies are not engaged in the IVC, the results show that the capital is lower in the network without any funding or large companies and the networks are less stable. This gives raise to the assumption that the AM webs of innovation system need higher financial resources to come to stable product development. The assumed high RRI cost will need extra financial resources to keep the RRI orientation high. Therefore, the innovation process needs additional financial resources for innovation. Innovation might stop completely as the networks without financial resources and without the engagement of large, financially strong companies. Additionally, the generated knowledge will not be published by open access and is not available for other innovations, even if the RRI inclination increases slightly.

The second simulation run shows a situation of high RRI costs and high funding where the capital of the innovation networks seems to be slightly higher compared with the previous one. Various networks were built in the idea generation phase, and a low number survived the product development phase. The results show that the financial resources were rather low, which is typical for a SME-driven system as in the early stage of AM innovations. A periodical breakdown of the innovation process can also be seen, with the revival of new ideas when there are no addition financial resources given to the system. This is considered as a typical feature for SME driven technological developments and is typical for AM (see developments of patents on 3D printing or AM, which are already know for 40 years, Ceulemans et al 2020).

The funding supported the innovation system and the capital is slightly higher, that innovation processes can be started but hardly brought in a later phase of product development or market diffusion. The potential of idea generation and early stage product development and networks is rather high, so that in a second innovation wave new networks and ideas start again. The RRI costs are high, so the RRI inclination is also high, but the potential to reach a successful innovation in the market diffusion phase is rather low, because of the imbalanced need of resource for RRI costs and innovation actions. Positive is that any new generation of innovation networks contribute to a stronger RRI orientation.

In the third round of simulation a situation of high RRI costs and a high number of large companies is analysed. This system behaves similarly as to the previous one (high RRI costs and high funding) until the transition to the product development phase, where these networks do not collapse, and the system is stable until the end of the simulation run. In the idea generation innovation phase, the RRI values showed linear behaviour whereas in the product development they increased stepwise.

From these results we can interpret that the high number of large companies bring more financial capital to the WIVC, which can be overserved by the higher capital of the network system. The number of the networks is stable, and the innovation idea can travel through the whole added value chain process. The relevance of SMEs for the creation of new ideas is highlighted.

Gaming Experiment - Mature AM Innovation System

This experiment simulates to a high extent the current situation of AM, which is characterized by a higher number of companies compared to research institutions, and by a higher number of customers. The number set in the experiments with relation to AM Tech is comparable to the AM Tech- companies today in the field of AM powder technologies, AM filament or AM lithographic technologies. With respect to materials, the number of suppliers is rather low, because currently the European market has a limit number of material supplier. Some parameters, such as funding or the number of big companies are modified to see if the behaviour of a more mature system is changed or can be compared to the early stage system. RRI cost are assumed again to be high, for showing a high RRI orientation to the society and the innovation system.

In the first simulation run a situation with high RRI costs, no funding, and a lack of large companies within the IVC is considered. The innovation system with the higher numbers becomes more complex but it is a rather dynamic system with, the capacities to generate new innovations networks in a second wave, but with those resources the probabilities to reach the market diffusion phase is low (although higher than in the 4th experiment). The rather high RRI costs seem to strongly prevent the growth of WIVC because of the lack of capital for innovation itself.

The second simulation run is based on a situation of high RRI costs, high funding, and the lack of large companies. The behaviour of such a system is similar to the previous run although the tendency shows a slightly higher number of networks. The system shows the capacity of rebuilding networks and funding can be considered a promoter of the stabilization of the system after its breakdown, although the number of networks and innovations that reach the market diffusion phase do not increase. Funding speeds up the dynamic of generation new innovation networks in the idea generation phase. The output with respect to open access increases significantly and due to the high RRI costs and the funding, the RRI inclination reaches high values, closed to the maximum for all defined RRI keys.

The third simulation run in this gaming session shows a situation of high RRI costs and 100% of large companies in the system. Increasing the number of large companies pumps enormous financial resources in the innovation system. Even at high number of networks, all pass the transition to market diffusion, the production of open access publication and formation of start-up is remarkable higher than in the second simulation run. The drawback is that that the model predicts hardly any new generation of new innovation networks. Therefore, the system does not show the characteristics to generate new ideas and innovation networks. Due to the high number of actors in the network, the average RRI inclination stays in the middle range.

3.4. Learnings from AM Future Scenarios

IAMRRI has conducted a foresight exercise where future strategies, future shapes, scenarios for the AM innovation system, for the AM dynamic webs of innovation value chains have been developed. This foresight process was applied to define future scenarios through co-creation by means of stakeholder workshops, focusing on how it supports the implementation of RRI aspects into additive manufacturing webs of innovation value-chains. The outcome of this process are four scenarios that represent a future vision of the AM WIVC in a time horizon of 20 years, including the description of how the different RRI keys would be considered and managed.

The IAMRRI foresight was organized in three workshops, with different stakeholders participating in each workshop. The foresight process co-created a common communicable and well-structured picture and awareness within the stakeholder groups about future shapes and strategies for AM and for WIVC in AM with openings for RRI through a diverse & inclusive, anticipative & reflective, open & transparent, and responsive & adaptive to change process.

In the next table a summary of the four scenarios created is offered (Hörlesberger et. al., 2021).

Table 1 Summary of the four AM scenarios

	SCENARIO	What is it about	AM connection
(A)	Responsible Europe	Sustaining AM system in a well-structured Europe	"Service Provider", consumer purchasing remains in conventional sales channels
(B)	Self-organizing society	AM maker communities and individuals	"Content Provider", consumer purchasing shifts to online file-sharing repositories
(C)	Elites of money and knowledge	Powerful and mature AM industry	"Market Explorer", Use of AM to enhance existing business models
(D)	Robots world	Artificial Intelligence serves the world	"Mass Customizer", use of AM to create new business models

Scenario A- Responsible Europe describes a future where there is a sustaining AM system in a well-structured Europe. In this scenario, openness and regulation ethical values, democracy, sustainability, and education are high values within policy and society.

RRI principles are implemented as high values, particularly through ethical values being implemented by means of standards and regulations. The design of the regulations according to ethical aspects depends on the people and experts developing this. When considering the medical application of AM, there are strict regulation making more complex to bring in new materials, new applications to the field. This is an advantage and safety for the patient However, it hinders new innovative approaches. Only larger corporations can go through the bureaucratic process.

Public engagement could take place by involving smaller groups that develop ideas, which is encouraged thanks to good education. Impulses for innovation from the society would be possible in design phase.

Science education is carried out by universities, high schools, and companies, increasing the innovation performance of AM. The training of society and increasing skills of workers triggers collaboration, accelerates innovation and new ideas. However, the number of women participating in the AM sectors is low, with women interested mainly in the design phase.

Data sharing and providing open access to knowledge is a risk for European companies, as only the EU pursues open science, while the United States and China do not pose those requirements on their research and innovation systems. Therefore, open science can accelerate innovation, but it is a risk if not done worldwide.

Scenario B- Self organising society describes a future where differentiation, democracy, individual solutions, and knowledge society are its main features. Individuality is the highest value of all, and individuals share a common understanding of high ethical values. In this context, precautionary principle is embedded into the innovation process and being very precautionary or proactive could create competitive advantage for companies, and desirable by the society. There is a highly ethical long-term thinking, which could be an advantage for AM technology compared to other technologies.

Public engagement happens via the individuals developing innovation but there is a lot of discrepancies between manufacturer and customer. Public engagement allows discussions with public that will dissolve the false expectations.

Science education is prerequisite for this kind of scenario and universities play a big role at the beginning. Companies also open up and give away knowledge and training so that they promote the technology and support the development of good-quality technology.

The creation of online platforms supports transparency and open access to knowledge and data, which also facilitates the engagement of different actors in the innovation processes.

Scenario C- Elites of money and knowledge describes a world of geographical and societal imbalances society is dominated by elites who own money and knowledge. Economy is dominated by only a few powerful enterprises. AM is a mature, highly automated, reliable, and efficient technology. The RRI principles are tried to be implemented top-down, but they are not of societal interest.

Ethical principles are defined by the elites, focusing on freedom as an important argument of innovation, which derives on exploitation of the poor by the rich. Public engagement is basically non-existent in this context and is prevented because of the danger of upheaval. However, highly educated people will get engaged in the innovation process.

Similarly, only elites have access to science education which impacts negatively on innovation since the number of actors in the innovation system is small. As for open science and gender equality, only when there is a benefit for the rich are those considered.

Scenario D- Robots world shows a world where smart systems are everywhere. Artificial intelligence (AI) and robots replace human beings in the production process and machines serve humans for wealth and prosperity. Data on humans is collected and used by the artificial intelligence. In this sense, RRI is part of the algorithm and people in force decide which RRI aspects are programmed into the artificial intelligence and robots.

Ethics is embedded in each stage of the innovation process, as the artificial intelligence includes an understanding of the ethics. However, there are unsolved questions such as the needs generated to the society by the artificial intelligence. In addition, there is no public engagement and laws provide regulations for society standards and the control function is carried out through politics.

Science education is implemented by artificial intelligence and robots and because of artificial intelligence overregulating, scientific interdisciplinarity declines. There is high specialisation of society on artificial intelligence and robots, which starts at higher education. The access to knowledge is easy.

Based on these scenarios, several relevant issues arise from the perspective of the risks and opportunities that those scenarios pose. First, regarding AM value chains on a high geographical level, we learn that if RRI was only implemented in Europe it could still be example for the world. However, when competing on a global market as AM does, strategies must be developed for bridging RRI and global competitiveness not to hinder the competitiveness of European companies.

Regulation shows two sides of the same coin. On the one hand, it can be beneficial for stabilizing AM technologies and processes and finding a common understanding on RRI among different AM actors. On the other hand, if taken too far regulation could hinder competition and decrease the diversity of actors within the WIVC, where only big players can respond to the regulation and consolidate in the market.

Open innovation and open access offer great opportunities for triggering innovation and enabling the existence of a wider heterogeneity of actors within the AM WICV, but we learn that knowledge sharing might not be enough and stable, long-term collaboration is needed to reach to getting the innovation ideas to the market.

Ethical thinking and the integration of ethical principles into regulation and standards is highlighted. This integration facilitates the mitigation of some of the technological risks posed in the future of AM and could provide a competitive advantage to AM technologies when compared to others.

Finally, the lack of science education and public engagement derives in a decrease in the innovation capacity of the AM WIVC because there is a low number of actors involved in the IVC. On the contrary, fostering science education, especially by companies, ensures highly skilled workforce in the future and consequently a high-quality technological development.

4. STRATEGIC RECOMMENDATIONS ON THE IMPLEMENTATION OF RRI OPENINGS IN THE WIVC

4.1. Openings for RRI within the AM WIVC

In this chapter we outline the openings for RRI identified by analysing the learnings from the research work in the IAMRRI project, with the ultimate aim of providing recommendations and guidelines for decision makers on how to implement RRI within the AM WIVC.

A. **Complexity of the AM innovation system and WIVC:** The complexity of webs of AM innovation value chains can result in losing sight of the socially desirable outcomes of innovations. In complex AM webs of IVCs, there is a need to delimit the scope of development to selected sections of the system (i.e., selected value chain levels that are operationally in the same maturity phase), to be able to validate the centrality of certain factors, RRI and their impact on innovation performance in real life settings. IAMRRI SKIN model helps to get better insight in the behaviour of complex systems such as WIVC in AM.

B. **Cooperation within AM WIVC:** In the IAMRRI project the barrier of competition was reduced by the funded project and the innovation process was in progress. A coopetition strategy especially in cooperation of various actor will lead to more successfully innovations. The collaboration between competitors with the objective of receiving mutual benefits could drive innovation more to the market. Companies that are keen to share their knowledge openly will attract more collaboration; get faster in developing trust with partners and perceive opportunities in other applications. Parallel potential failures can mitigate in the future.

C. **Cross-fertilisation of RRI within the AM WIVC:** RRI committed organisations operating in many different value chains enhance the spreading of RRI when they explicitly push it and have it implemented in general in their business processes (institutional change). Those organisations would act as triggers for the adoption of RRI principles by other actors within the WIVC.

D. **RRI as a new paradigm in innovation:** As companies become aware of their benefits in contributing to the development and well-being of society through responsible innovation, a new way of thinking, acting, collaborating and thus innovating is emerging. RRI is part of this innovation paradigm where companies anticipate the future and understand the dynamics between innovation and its impact on society.

E. **Coordination advantage:** The shorter life cycle of novel AM products and their innovation poses a challenge for the innovation system when RRI has to be implemented from scratch on a recurring basis. Criss-crossing in the AM WIVC offer an opportunity to come to a more efficient RRI innovation. An optimal solution will be a better coordination between different organisations and an adjustment of interrelated innovation in the different topics such as material, machine and application. Interrelated innovations have to be coordinated with respect to timelines.

F. **Heterogeneity:** Diversity and heterogeneity of actors within the WIVC enables the creation of ideas and facilitates the exchange of knowledge from multiple sources. The bigger and more diverse the networks are, the more possibilities for interesting collaborations arise. In this sense, RRI also plays a key role, as a high RRI inclination of the network actors (such as e.g.

open access and public engagement) drives a higher heterogeneity of the WIVC, because other innovation partners are attracted.

G. **RRI costs:** High RRI costs decrease the number of networks, increasing resources for compensating RRI costs, which correspond to an increase of the capital of the innovation system. This compensation could lead again to an increase of the number of innovation networks. In addition, high RRI costs with no compensation of financial resources seem to hinder strongly the growth of WIVC. Public funding could be an instrument to tackle with this on innovation project level.

H. **Competition in a global market**: The European AM companies operate in a global market. For international businesses, making profits is still the most important KPI. In this context, considering RRI poses a big challenge to the companies, where market success seems to be still in contradiction to social orientation. A change of business success paradigm is needed with regard to the societal orientation, where it is considered a competitive advantage of companies rather than a burden.

I. **Understanding of RRI:** RRI has been introduced as an umbrella for different societal topics, which are themselves complex and broad. This complexity hinders the understanding and implementation of RRI principles mainly by companies, which do not see the benefits and miss knowledge and information about RRI. However, companies have routines and protocols that could be enhanced with RRI, such as risk management, environmental management or health and safety management. RRI needs to liaise with the strategy of the organisations and RRI-related capacities and resources need to be provided.

J. **Specific RRI keys:** some of the RRI keys are important drivers for innovation within the AM WIVC, such as open access and public engagement. However, they pose significant difficulties for some of the actors involved in those webs, particularly to firms. The need to protect their key knowledge derives in the reluctancy of firms providing open access to the data and knowledge, while they take advantage of it when searching for knowledge or new partners in their networks. Similarly, public engagement is somehow neglected by AM companies who mainly operate at business-to-business level and do not consider that the engagement with civil society is needed. Nevertheless, the relevance of the collaboration with universities, research institutions and intermediary organisations is highlighted by them.

K. **Universities and research institutions:** the collaboration and interaction with universities and research institutions upgrade the RRI-related capabilities of companies and adoption of RRI practices, specially favouring the science education activities and orientation of companies.

4.2. Recommendations for implementing RRI within AM WIVC

Based on the learnings derived from IAMRRI research and the openings for RRI within the AM WIVC the following recommendations for the implementation of RRI within those webs.

Table 2 Recommendation 1 - Reinforce the implementation of RRI at early stage of the innovation process

IAMRRI recommendation- Reinforce the implementation of RRI at early stage of the innovation process
RRI affects early stages of the technology innovation developments like AM innovation strong. Relevant phases are the idea generation and research phases, in which is more freedom in decision making and the risk for integrating RRI considerations is rather low. The potential for influencing the innovation is in contrast very high. In addition, cooperation among companies at early stages of the innovation phase happens more easily as they share knowledge more freely. Therefore, funding organisations play a key role in setting the requirements for introducing RRI at early stages for technological innovations such in AM. In addition, further opportunities for introducing RRI arise in the gate that opens between the idea generation phase and the idea development phase, where RRI criteria or standards could act as gate keepers. The goal to implement RRI in early stage innovation have to be coupled with extra funding for RRI actions.
Target group: funding organisations, policy makers

Table 3 Recommendation 2-Keep RRI costs for the actors within the AM WIVC low

IAMRRI recommendation- Keep RRI costs for the actors within the AM WIVC low
Investing in RRI has a cost aspect for innovating actors and can when are getting high, reduce the number and diversity of actors within the AM WIVC and that of innovation networks. However, a sufficient RRI orientation (and RRI cost) of the actors and a balance composition of the networks with the participation of creative SMEs and the financial resources of strong companies lead to a higher potential of successful innovations that drive the AM innovation system. Among the different measures that could be implemented innovation funding is an excellent instrument to support the idea generation and early stage of product development, reducing the obstacles that high RRI costs could pose for the innovation system. RRI thinking could also be increased through a higher engagement of universities and research institutions in the IVC. Those institutions have a stronger RRI-orientation and could facilitate the adoption of RRI practices within firms. Learning effects on RRI can reduce the RRI costs at firm level.
Target group: funding organisations, policy makers, research institutions, universities, transfer – units e.g. clusters, firm and science organization are active in AM

Table 4 Recommendation 3- Combine regulation and standardisation

IAMRRI recommendation- Combine regulation and standardisation
Too strict regulation can slow down innovation in early stages of technology development and reduces the heterogeneity of the actors within AM WIVC, as well as the inclusiveness and number of collaborative networks. However, if done carefully and appropriately regulation can foster the diffusion of RRI practices and the creation of diverse and inclusive networks. It is thus essential to find a balance for regulation AM WIVC. In this sense, making European societal norms and values transparent and clear; so it can be avoided that any novel technology development such as AM, become overburden with regulation. The society can easily follow that principles and join the RRI dialog. The creation of a common playing field for all the actors involved in AM WIVC can also be through a standardization process or by creating voluntary codes of conduct for the actors, particularly for the companies within those webs. As there are not yet dominant designs, standardization enables conducting a self-regulating bottom-up process, where all the actors involved discuss and agree upon shared values and understanding and define how RRI should be implemented.
Target group: regulatory bodies, standardization organisations, policy makers, industrial associations and clusters, community of AM firms, public

Table 5 Recommendation 4 - Strengthen collaboration within AM WIVC

IAMRRI recommendation- Strengthen collaboration within AM WIVC
In the context of AM collaboration is a challenging and critical issue. It enables the heterogeneity and diversity of IVC and sparks innovation creating a unique set of knowledge, skills, and expertise to the WIVC. However, any successful collaboration needs a well-developed trust. Here, RRI keys such as open access may help to facilitate the collaboration. Companies that are keen to share their knowledge openly will attract more collaboration, faster in developing trust with partners and potential opportunities in other applications. At the same time, potential failure in the future can be mitigated. Some of the stakeholders within the WIVC, such as industrial associations and clusters, have a relevant role in building trust and bridges among firms and between those and other relevant organisations such as universities and research institutions. This facilitator role can be complemented by acting as "RRI ambassadors" and promoting the implementation of RRI in firms.
Target group: industrial associations and clusters, AM companies, universities and research institutions, knowledge and technology transfer units

Table 6 Recommendation 5- Underpin public engagement in AM WIVC

IAMRRI recommendation- Underpin public engagement in AM WIVC
In an EU policy context where citizen engagement in research and innovation activities is being specifically addressed, the reinforcement of implementation of the public engagement key in AM WIVC is needed. Public engagement needs to be integrated in the early stages of the innovation process, so that considerations outside the "scientific bubble" are taken into account and relevant societal issues are identified. Moreover, stakeholder engagement should not be a one-way solution but a dialogue where research institutions and companies pose questions to civil society and civil society learns from those organisations. Stakeholders should be involved in societal-technological assessments or scenario developments such as in a foresight. Supporting public engagement through funding and incentives is an option but it needs to be supported by other measures related to science education, in order to have a meaningful and enriching dialogue between the research world and society. Also, resources need to be provided for training and capacitation for research institutions and companies to carry out public engagement actions. Companies, especially SMEs might struggle organising public engagement processes and attracting external stakeholders. In this sense, the role of organisations such as technology transfer units, clusters and industrial organisations that have the capacities of attracting different actors and stakeholders within and outside the AM WIVC is highly relevant.
Target group: policy makers, funding organisations, AM companies, industrial associations and clusters, civil society, researcher and scientists

Table 7 Recommendation 6- Increase RRI capacities of AM actors and society

IAMRRI recommendation- Increase RRI capacities of AM actors and society
The companies within the AM WIVC need financial resources for implementing RRI into their research and innovation processes. However, and maybe more importantly, they need to build the organisational and knowledge capacities to shift from an economic business orientation to a socio-economic business orientation (intuitional change). There is a need to change the mind-set and to integrate high ethical values of society within the actors, company leaders and employees in technological innovations such as AM. RRI capacities of those actors need to be increased and higher education plays a key role in this sense, offering the opportunity to integrate RRI-related topics in the educational curricula (especially in science and technology) and fostering diverse and critical thinking. Linking RRI with Sustainable Development Goals could facilitate the transformation of existing understanding, let RRI become an added value for organisations and society. In addition, science education and educating society on technological aspects is a clear driver for innovation and triggers the integration of the other RRI keys with the AM WIVC. Pin down new social-economic orientation in standards. Develop instruments and set out programs to make RRI thinking to an integral element in future technology developments such as AM, widen the approach of the implementation of RRI in organisations via research and innovation action
Target group: policy makers, universities and other education providers, industrial associations and clusters, standardisation organisations

5. RECOMMENDATION FOR FUTURE RESEARCH DIRECTIONS

Throughout the different research activities of IAMRRI several research topics represented by the different outcomes of the IAMRRI project several opportunities for further research and knowledge development can be found. In general, all are triggered by the new European Green Deal strategy which will have a strong impact on technology development, as seen through the webs of innovation value chains on the example of AM.

On the one hand, referring to the WIVC such as AM, there is a need to further research on the exploration of the exact episodes and events where RRI-oriented routines could be useful in firms and in their relationships with respect to their innovation processes, behaviour and outcomes. On the other hand, regarding the IAMRRI SKIN model, it is important that the model will be used, experimented, and extended in the scientific community and policy makers. It is essential to let other researchers replicate the model, to extend it, to discover other behaviours, or observing new properties emerging from bottom up. Currently the model is referred to two industries - automotive and medical. It could be very interesting to apply the model to different industrial sectors or other technologies. For that modified data are needed.

It is also important to keep in mind that ABM is a tool for thinking, not for prediction. Gaming is a new way to understand the mechanisms in complex systems. Observing the results from simulation lead to reflection on the implication behind it. A continuing dialogue with the users and other science disciplines should help to gain an in-depth understanding about the model results and what the implications are for policies. This needs a close link to conceptual research and the performance of studies as mentioned below. ABM represents an effective method of integrating real-world data and complexity into a model, and is a future research field in system analysis of complex innovation developments combing engineering sciences and social sciences. Collecting and analysing of data from real systems help to verify and validate the models. This needs extensive co-operations of various science disciplines. Agent base modelling and simulation can become a virtual test bed for new technologies addressing topics like climate neutrality and society or increasing of resilience of complex eco-societal systems and help to find strategic recommendations.

Typical further research fields are proposed

Apply modelling and simulation

- Improving and strengthening the modelling and simulation of new technology innovation systems to get deeper, holistic and more efficient insight in future developments in first step and derive in cooperation with the conceptual thinking the relevant indicators. Take actions in the technology assessments; include modelling in simulation in many as possible research and innovation initiatives in societal/technology interrelation.

- Develop a conceptual understanding and a development of relevant indicator bases on outcome of **simulations** for monitoring the innovation development especially in web of innovation value chains.

- Encourage the community of conceptual systems research of complex systems to start a closer cooperation with the modelling community, to speed up knowledge creation, use gaming experiment to understand complex system on a profound and holistic level.

Mapping and studies

- Mapping, categorizing and prioritizing the qualitative antecedent factors within and across AM innovation project types (possibly by comparing across projects differing in their impacts). Collect the relevant data

- In-depth case studies on early adopters of new technologies such as AM to clarify the path from AM adoption and business case selection to the different dimensions of market and strategic impact. Derive the relevant data sets.

- Comparative studies across different technology innovation project types, to understand how the conceptual framework varies across project types and contexts. Forster cooperation of different field of science research, derive also the relevant data sets.

- Exploratory and in-depth studies about AM-related service offerings, their development, and market and strategic impacts, expand to other upcoming technologies

Supporting research - Co-creation with stakeholders

- Develop in co-creation with society new scenarios of the future to open up the mind of the society, which supports holistic thinking at any new technology development.

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