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I AM RRI

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

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D2.4 Final conceptual model on web of innovation value chains in additive manufacturing

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Abstract: This report summarizes current-state knowledge on the webs of innovation value chains and innovation performance in additive manufacturing. It points out key priorities in the antecedents of different performance indicators and shows tentative evidence of the functioning of IVCs, through innovation examples of automotive and medical sectors.

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Contents

1. Introduction

This report summarizes current-state knowledge on the webs of innovation value chains (IVC) in additive manufacturing (AM), building upon and upgrading I AM RRI D2.3 (also D2.1 and D2.2) and including feedback and input from practitioners on the real innovation value chains and their webs. The report offers additional details concerning the measures of the antecedent factors and performance indicators relevant to the innovation value chains and possibilities for the openings for responsible research and innovations (RRI). The report builds a foundation for simulating and testing the conceptual model. As the literature offers merely partial evidence on the aspects of the model and also the practitioner interviews have covered partial innovation value chains only, the conceptual model requires further development during the forthcoming phases of the project (in WP3, WP4 and WP5), as indicated in the project plan.

The starting point for this report is the previous deliverable D2.3 that showed how the tentative actor-stakeholder-network maps were specified and what kinds of innovation value chains exist in AM, primarily based on literature and collaborative work among the project partners. We build on these early findings, continue with a similar design science approach and specifically add evidence concerning the IVCs in AM and explain how RRI can be included in the model on webs of IVCs. To add to D2.3, additional data were collected through the workshops organized in I AM RRI project, a stakeholder survey conducted in WP6 (and reported in D6.2), and interviews held with practitioner partners involved with different AM innovations. These sources of information were used, to further develop the conceptual model designed concerning the webs of IVC and the logic through which RRI may influence performance.

The key outcome of this report is understanding on the nature and connectedness of AM IVCs and on the possibilities for RRI openings to enhance innovation performance in webs of IVCs. The report next summarizes the conceptual framework reported in D2.3 as a starting point for further development, including its main components (innovation value chains and their webs, innovation types, actors and stakeholders, factor categories, and innovation performance in AM and prioritization of key factors as antecedents to innovation performance. Then, key aspects of RRI are introduced to be included in the model. In the fifth chapter, real life examples are introduced of AM innovations in the different sections of the webs of innovation value chains. Tentative empirical understanding is shown both as part of specific types of innovations and their related IVCs, and on how the ‘criss-crossing’ between the IVCs occurs. The conceptual model is then built and reported, based on the work done so far, and possibilities for the openings of RRI in the IVCs are summarized. We then discuss the key learnings, choices and assumptions concerning the model. The report ends with conclusions.

2. Conceptual framework on performance in AM webs of innovation value chains

2.1 Overview to the conceptual framework

The starting point for the development of the conceptual model here is the tentative work done for deliverables D2.1, D2.2 and D2.3. The framework concerning antecedents and performance consequences of the webs of IVCs include factors relevant to actors and processes and how they determine outcomes in terms of economic, social and strategic impact. This project seeks to understand how certain factors influence outcomes, as they work through and are mediated by the specific industry structures and processes of AM. In particular, the interest is in where openings for RRI exist as part of the webs of IVCs. Figure 1 summarizes the conceptual framework, to which details are offered in the following chapters.

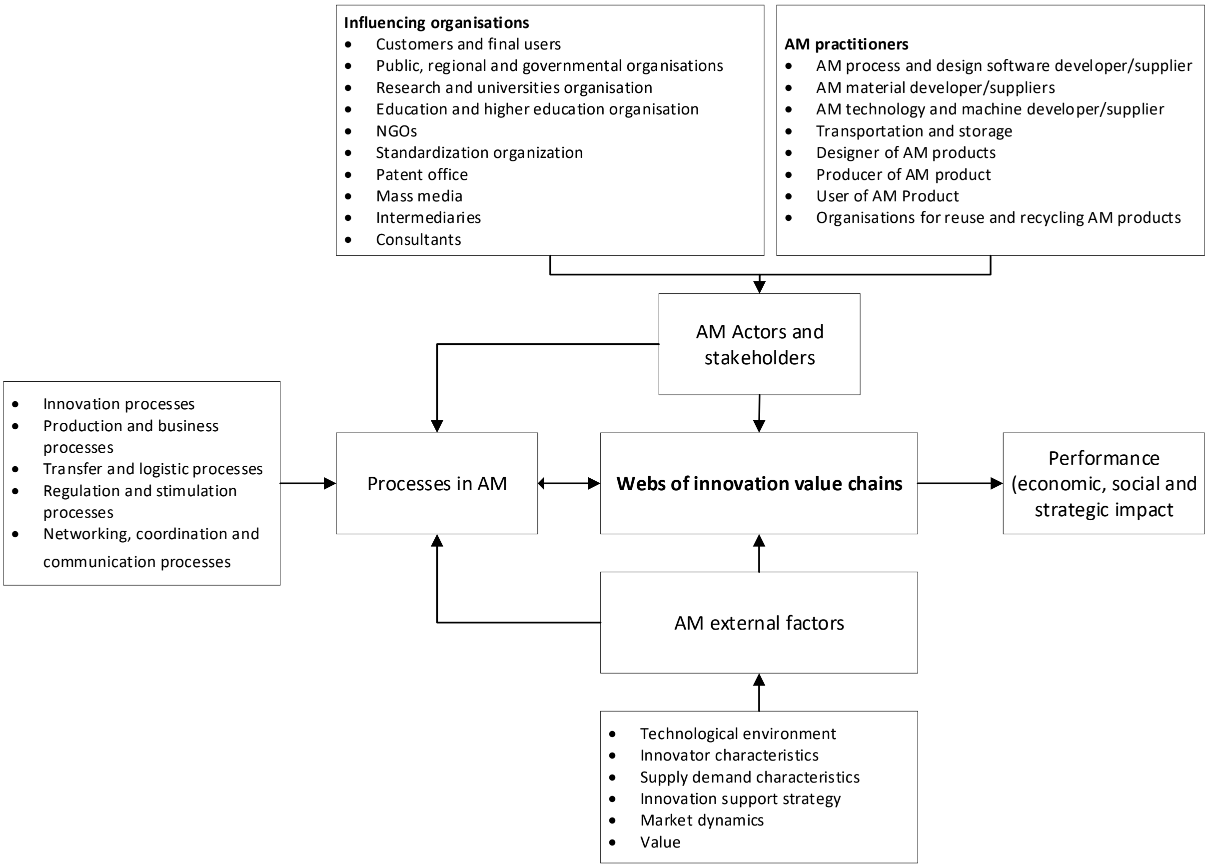

Figure 1: The framework for defining processes, performance, factors and actors of webs of innovation value chains

The framework consists of four main elements surrounding webs of IVCs: external factors, actors and stakeholders, processes, and performance as the outcomes of IVC-related processes. In this framework, performance is assessed in terms of economic, social and strategic impact. The external factors need to be considered as they have direct and indirect influence on webs of IVC, and those factors include technological development, characteristics of the innovators and business, supply chain, innovation strategy, market dynamic and institutional value. Actors and stakeholders concern the organizations involved in AM, while the processes deal with value-adding activities of and between the actors and stakeholders. These issues together form the innovation networks where knowledge, material and services may flow between different innovation value chains (open access). In the following chapters we will report how the main aspects of this framework have been developed, towards a conceptual model.

2.2 Overview to innovation value networks and sectoral innovation systems

Innovation is increasingly being created in collaboration with a number of actors (Tsai et al., 2009; Powell et al., 1996). Knowledge creation is the primarily motivation for collaboration (Cohen and Levinthal, 1990; De Clercq and Dimov, 2008). An innovation system consists of a set of actors or entities such as companies and further organizations. These actors interact while creating, developing, and diffusing new knowledge, product ideas and economically useful products. The innovation system approach provides a useful framework to understand why some companies, sectors or regions are economically more successful than others.

Various scholars have focused on studying why firms participate in **innovation networks** (Kogut, 1988; Hamel et al., 1989). One of these antecedents is that by cooperating firms can spread risks and increase individual uncertainty (Gulati & Gariulo, 1999). If applied to the case of AM, by sharing manufacturing equipment or machinery that often require a large investment, risks can be spread. That is why companies start cooperation. Another reason why firms engage in inter-organizational relationships is for the sake of (inter-organizational) learning (Hamel et al., 1989; Hamel, 1991). When we apply this to the case of AM, by engaging in innovation networks, firms can learn from each other and incorporate the new knowledge into their innovation processes. A third reason to establish innovation networks is to establish common standards. In markets that are characterized by increasing returns to adoption, technologies increase in value the more they are being adopted by users (network effects) (Farrell & Saloner, 1985; Katz & Shapiro, 1985). In such markets, de-facto standards can often quickly arise where users get locked into one de-facto standard. From an RRI perspective this might lead to market acceptance of technologies that are not socially accepted. One way to counteract that situation, is to form innovation networks and engage in committee-based standardization. By involving a large range of stakeholders in the innovation networks collective action can be increased and it is expected that social acceptance also increases.

Innovation networks may cross industry boundaries, but it is necessary to understand the industries and related boundaries because each industry sector has its own **sectoral systems**, in terms of the knowledge base, technology, demand, and even culture and dynamics (Malerba, 2002). Sectoral systems are governed through the institutional structures, norms and rules specific to that industry, and organizations within a specific industry need to operate under such norms and rules (Malerba, 2002).

Additive manufacturing is considered as a sectoral innovation system. Such a sectoral innovation system is characterized by interdependent actors and their interactions, which are non-linear. Sectoral innovation systems are investigated by various authors (McKelvey et al. 2007, Arthur et al 1997, Nijkamp et al. 2001, Katz 2006). A sectoral innovation system is formed by organizations such as companies and research institutes, and firms utilizing the technology (Breschi and Malerba, 1997; Malerba, 2002). For example, Korber et al. (2009) described the sectoral innovation system for biotechnology.

The earlier report, D2.3, devoted a considerable amount of space to clarifying the concept of Innovation Value Chains (IVCs) and to the notion of Webs of Innovation Value Chain (WIVCs), which comprise intersecting IVCs and in our view represents the innovation network, possibly involving multiple linked sectoral systems.

Our purpose here, then, is to take further steps toward understanding the logic of how the internal characteristics of the AM IVC and the external factors affecting it combine to give rise to performance outcomes. At this stage, this logic is still hypothesized and imputed, based on the literature, other secondary sources, and our early engagement with industry partners and other stakeholders. The forthcoming in-depth use-cases to be developed in WP4, will allow us to understand in detail the conditions and processes of innovation, with their attendant openings for RRI, and how they may be connected to the performance outcomes we aim to engender.

2.3 Phases in the innovation value chain

According to the I AM RRI project plan, the research links IVCs with each other in the attempt to achieve performance impacts. A central underlying idea is that innovation is an invention that is brought to the market, and in the context of AM it has also relevant effects in the society and requires value-adding activities by multiple different organizations. The value chain is defined as 'a sequence of activities during which value is added to a new product or service as it makes its way from invention to final distribution.' (Botkin and Matthews 1992, p.26).

For I AM RRI project, **IVC** is not described through separate stages of innovation but rather through **non-linear phases involving multiple organizations and separated by critical junctures**, decision making points. Hansen and Birkinshaw (2007)'s definition is widely used and offers the closest proximity to a formal definition of IVC: "The innovation value chain view presents innovation as a sequential, three-phase process that involves idea generation, idea development, and the diffusion of developed concepts. Across all the phases, managers must perform six critical tasks – internal sourcing, cross-unit sourcing, external sourcing, selection, development, and company-wide spread of the idea. Each is a link in the chain' (Hansen and Birkinshaw, 2007: 122). It is important for the organizations involved to overcome the critical junctures to progress towards the next phase of the innovation value chain. The innovation can stay in one phase as long as there is no pressure or support to move to the next phase. Borrowing the definition for Hansen and Birkinshaw (2007), IVCs also in this study proceed in three main phases:

- Phase 1: idea generation;
- Phase 2: product/idea development[1];
- Phase 3: innovation diffusion.

In the first phase, ideas emerge, are conceived and presented. In some cases, innovation can start from basic or applied research at universities or research institutes; it can start from technology suppliers or manufacturers; or sometimes innovation can also start from user or market. Roper et al. (2008) identified the following possible ways to generate idea: New requirements (law), new request (forward linkage - customer), internal invention, collaborative invention (backward linkage – with supplier), open innovation (public linkage - getting input for innovation from research institutes or universities; this includes innovations from societal perspective utilized by funding) and invention imitation from the competitors (horizontal linkage). Roper et al. (2008) argue that different ways to generate requirements have their own probabilities and weights (New requirement will not happen as often as customer request, but law requirement has greater weight).

With sufficient potential, the idea may move to phase 2; through successful development it can move to phase 3. In our understanding, this IVC involves multiple organizations in each phase, the number

[1] Named in I AM RRI project as idea development

of organizations can change from one phase to the other, and there is iteration and feedback loops both within and between phases. Figure 2 illustrates the connections between the phases of the IVC.

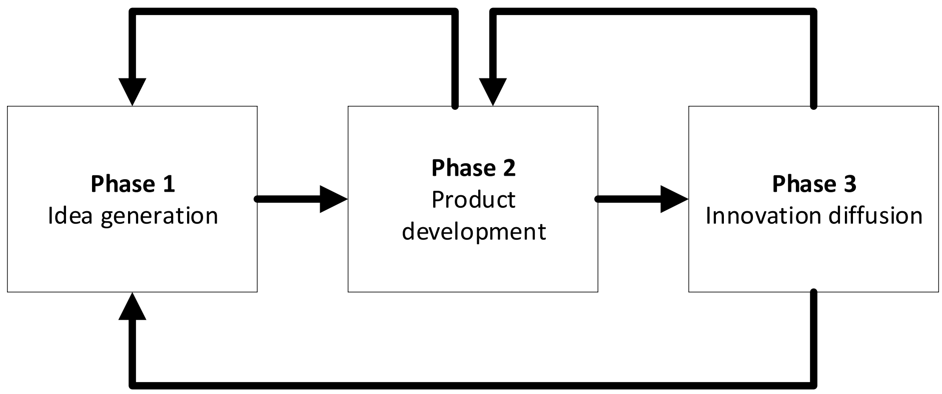

Figure 2: Innovation value chain with feedback loops

Innovation activities are carried out by actors. One actor may carry out more than one activity. More than one actor may be involved in each phase of the IVC, and any actors may be involved in more than one IVC phase. An important aspect of the IVC is the nature, content and strength of the transfers and interactions between actors within IVC phases, and between IVC phases. Innovation value chains comprise of knowledge sourcing, knowledge transformation and exploitation (Roper et al., 2006). A company first sources knowledge either from within its own organization or through other firms, then transforms it into an innovation and then tries to exploit the innovation (Roper et al., 2006). Knowledge is exchanged between the actors. Every actor in the IVC is not involved in all of the three phases and most of the innovation activities are knowledge sourcing and integrating knowledge from different sources (transforming into new knowledge). The relevant tangibles exchanged in terms of knowledge exploitation are physical objects, software and digital models. The output of the idea generation phase can be for example a documented development plan that becomes an input for the idea development phase; it can be exploited multiple times, and fed back to the previous phase for further knowledge sourcing, integration and transformation.

As mentioned above, we see each of the IVC phases as a networked effort and, thereby, also the concept of value networks is relevant (Carter et al., 2002). Webs of IVCs, then, are inter-dependent chains of innovation activities that span multiple organizations. 'Criss-crossing' or connected IVCs are inter-dependent because at some point they draw on the same resources and are carried out by the same actors, although not necessarily at the same time.

2.4 Types of innovation in AM

For the purpose of making the abstraction of innovation value chains more tangible we identified five different innovation types relevant to AM, and they are presented below. Each of these innovation types represent their own sector, with a specific knowledge base, process, technology, and cultural dynamics. However, these sectors will need to cooperate and they are interdependent, for the AM innovations to succeed. The main idea behind this division of innovations into separate contexts is to address the main features of AM industry and build a logical structure for the webs of IVCs in that context. The different innovation types in the webs of IVCs are the following:

1. **Product produced by AM** that is mainly driven by the demand and use of the AM products. This level includes the actors that use the AM products or are the customers (buyers) for AM products. The customers may be multiple different organizations (actors), due to the common need to integrate multiple components into a full final product.
2. **AM digitalization and software** are a very important level at this point of the emerging AM technology both for the supply chain and for the innovations. Both the product's digital design and software design are acknowledged. Software development includes software development for the AM machines and for AM design. Again, multiple different organizations may be needed, depending on their scope of business.
3. **AM services** covers the AM production, beginning from the AM feedstock manufacturing until the finished AM product and its distribution. Sometimes a single firm may cover a large part of the production process and only source material supply and transport from other firms, but sometimes also the production tasks are divided across different organizations.
4. **AM machines and technologies** are a critical resource for AM production, and as the technology is currently evolving and non-standardized, its position in the AM innovations is quite relevant.
5. **AM materials** are also a critical resource for AM production, and as the technology and materials are currently evolving, its position in the AM innovations is quite relevant.

To describe the actors, interactions, factors and performance indicators, the project has created an excel file covering such aspects that have either been identified in the literature review or in the workshops and interviews of this project. However, not all of the actors identified participate actively within IVCs, even if they may have an otherwise active role in the supply chain. Some actors are more relevant in creating innovations and play a significant role depending on the context and phase of the IVC.

Different actors interact with each other both within an industry sector and between industry sectors for different purposes. The interactions may take the form of commercial exchange (e.g. selling, procuring, delivering, receiving), or non-commercial collaboration (e.g. learning, knowledge exchange, joint research), and both of these are relevant in AM IVCs. The interactions may occur between two firms, or between multiple firms, and all firms may have some expectations toward each other. Particularly in the commercial exchanges these expectations are governed through contracts that include also incentives and sanctions associated with fulfilling the expectations. In any of these settings the distribution of power may vary so that sometimes a certain firm dominates and rules the interaction, whereas others are reactive and followers. In this study, we are particularly interested in the behaviours (actions, activities) of certain agents, as well as the flow of information/knowledge between the agents in the interactions.

2.5 Actors and stakeholders the innovation value chains

Both general and sector-specific data-collection activities have allowed us to identify a number of typical likely actors in various stages of the innovation value chain. For this purpose, the project has conducted several workshops aiming to identify actors who are involved in innovation activity. Table 1 portrays actors and their behaviour and objective within the IVC. The majority of the identified actors have a role in both AM supply chains and IVCs. In addition, some secondary stakeholders were identified that do not take part in the manufacturing supply chain of AM products or services, but their interactions with other actors are significant in guiding the innovations toward desirable performance outcomes. These actions may deal with incentives, requirements or markets, e.g., through standards, patents and regulations.

For the purposes of modelling, the actors and stakeholders will be conceived of as agents, acting according to behavioural rules and influenced according to external factors. For the purposes of modelling, the focus is on the interactions between actors, the content of the relationships between them, and the strength of the effect on performance of one agent's action on another. This is characterised for each stage of the IVC. So, for example, the primary content of a research institute's interaction with an AM manufacturer is the transfer of information; the more information that is transferred (stronger interaction), the better the technical performance of the innovation process stage (which could be idea generation or idea conversion in our standard IVC model). The RRI theme of open science can be included in the modelling of such a relationship or interaction: the adoption of open science by the research institute could be reflected by a greater transfer of information.

Table 1. Examples of actors and stakeholders in AM industry according the investigation of the actors-stakeholder networks.

name of actors	descriptions
AM technology company (firm)	A firm that owns AM equipment and uses AM as part of its manufacturing process. The firm may have also other roles in the supply chain, such as design and post-processing. The objective of AM technology companies is to serve the value chain by providing support, product and service. The general rule for any commercial company is to maximise profit and minimize cost.
supplier (firm)	An organization that supplies raw material, components or services to another organization (for money or other benefits). The objective of external supplier companies is to serve the value chain by providing support, product and service. The general rule for any commercial company is to maximise profit and minimize cost.
OEM product designer (firm)	The objective of OEM (original equipment manufacturer) product design company is to meet demands from market and the end users. The general rule for any commercial company is to maximise profit and minimize cost.
customer (firm)	An organization or individual that receives AM products or services from AM firms and use them in their business (toward end-users).
end-user (part of society)	An organization or individual that uses the products (or services) delivered in the AM supply chain.
research institute/universities (knowledge provider)	An organization that offers research and development. May be public (e.g. university, college, etc.) or private (private research organizations). Research institutes/universities conduct research to gain knowledge and develop the technology by exploiting and exploring new material, application and technology.
regulators (patent office) (stakeholder)	Provide protection to intellectual property and ensure that the industry meets minimum requirements. Provide protection to the end users by setting the standards.

name of actors	descriptions
financing institutions (e.g. banks) (stake-holder)	Firms that facilitate the exchange of equity ownership, or research and development, for instance, in the form of loans, funding, investment support, and development support. Support the industry by providing loans.
insurance firms (stake-holder)	Firms that offer insurances to other organizations and individuals. Pub-lic health insurance companies also included. The insurance firms re-duce the risk of developing technology and uncertainty in market de-mand.
government/politi-cian/public authorities (stakeholder)	Political decision makers for the society (law, regulations) and the eco-nomic system of European, nations and region, actors of democratic systems
funding organisations (stakeholder)	Manage funding programs, provide financial support, define conditions and processes for funding, European, national or regional activities, in close cooperation with public authorities, support innovation action ac-cording to European regulations and certain technology readiness lev-els.
standardisation organi-sations (stakeholder)	Develop rules and processes for new technologies and products to guaranty unique standard of products, in most cases technology ori-ented by also to internal structures like quality management of Cooper-ate social responsibility
educational/training in-stitutions (knowledge provider)	An organization that offers education, studies and training services. May be pub-lic (e.g. university, college, etc.) or private (educational firms). Provide skilled employees and educate market about the poten-tial use of AM technology.

The innovation value chain consists of these kinds of actors. In each of the three phases in the innovation value chain (idea generation, idea development, and innovation diffusion) the collaboration activities can be illustrated via actor networks, where knowledge creation takes place. These networks in each phase are connected to the whole innovation network. The network inside the three phases differ in the types of organizations involved. The first phase (idea generation) is dominated by scientific and research organizations such as universities in collaboration with high tech firms, not excluding organizations which support with services or are needed for stakeholder dialogues. In the second phase (idea development) the created knowledge in the first phase in transferred into a solution (potentially a product), where mainly production companies are engaged. In the third phase (innovation diffusion) other business firms are active. There are, of course, other organization types in each phase, however, the dominating ones are mentioned here.

2.6 Factor categories relevant to AM innovation value chains

Several categories of factors were identified to influence the IVC performance. Based on literature review and data collection process, several factor categories were listed and are shown in table 2. They are assumed to be influential in determining the characteristics and performance of IVC. Chapter 2.8 goes further to summarize the priorities among single factors, derived from these factor categories.

Table 2. Influential categories of factors in AM industry.

name of factor category	descriptions
market, customers and competitors	Dynamic and unpredictable. The behaviour of factors in this category is influenced by many factors.
product characteristics	To meet certain characteristics such as user friendliness, compatibility, durability, accessibility, etc.
organization, strategy and knowledge production	Maximize profits, minimize costs
technology	User friendliness, compatibility, durability, accessibility, etc.
production and operation	Maximise profits, minimize costs
RRI	RRI keys such as gender equality, science education, public engagement, open access, ethics, and governance.
megatrends	Global factors that may influence the AM industry as a result of increasing or decreasing level of resources
local context	Want to achieve local competitive advantages

Note: the listed categories represent an accumulation of several factors with similar behaviours.

Were such an innovation process understood to take place in the idea generation stage, the outcome of this interaction can then be treated as a supply of ideas to the next stage – idea conversion, or product/idea development, in our adopted IVC model.

As part of industry foresight work in this project, stakeholders of IVCs in AM were inquired for their perceptions of influential aspects on additive manufacturing through a survey (reported with detail in Hörlesberger et al., 2019). The respondents included primarily universities and industry in the automotive and medical sectors. The survey revealed that the two industry sectors portray slightly different viewpoints regarding which aspects are relevant in influencing AM. Table 3 summarizes top two aspects per thematic category, as studied in the survey.

Table 3. Summary of stakeholders' experiences of aspects influencing AM: top two influencers/aspect (summarized from Hörlesberger et al., 2019)

aspects influencing AM	automotive sector	medical sector
technology	• sufficient maturity of printing technologies • availability of affordable and mature 3D printers	• availability of different and sufficient printable materials • sufficient maturity of printing technologies

aspects influencing AM	automotive sector	medical sector
product design	• possibility for complicated component geometries • advanced tooling and prototyping possibilities	• possibility for complicated component geometries • design freedom
consumer demands	• Demand for specific applications in high-price segments • Customized products	• customized products • higher awareness of advantages
economic aspects	• cheaper and efficient production • lower logistics expenses	• new business models • lower logistics expenses
political aspects	• funding possibilities • environmental policy	• standards and norms • funding possibilities
social and ethical aspects	• image as future technology • educated and skilled workforce available	• educated and skilled workforce available • trust and social acceptance of products • sufficient education and skills development

2.7 Innovation performance

Defining and measuring the performance of an innovation such as AM is crucial, both practically and scientifically.

Practically both managers and policy makers need to know the performance of an innovation. Policy makers need to track the effect of their policies and other interventions on the performance of an ecosystem around an innovation. From the perspective of a policy maker performance can be defined and operationalized in terms of the effect on society, for example in terms of preserving the environment, or in terms of job creation. From the perspective of managers, the performance of an innovation can be defined and operationalized in terms of the profit generated by their company or the growth and average profitability of the entire network of companies involved. All of these performance aspects can be subdivided in three main key performance indicators: strategic impact (including job creation just mentioned), social impact (including sustainability) and economic impact (including profitability and growth).

Scientifically the innovation performance is playing a central role to explore which independent variables, be it technology characteristics, company strategies, ecosystem structure or government policies, have a significant influence on (or relationship with) the performance of the entire ecosystem. Knowing the relative influence of so-called independent variables, either because they have the strongest positive or negative effect on performance or because these variables are part of an interactive loop of reinforcing mechanisms, helps to choose and shape conditions that favor the innovations positive effect on society or its positive effect on company performance, as measured in profits and growth, for example.

Firstly, the performance indicators should be useful for entirely different actors such as company managers and policy makers. For company managers a government policy performance aspect, the influence of a specific policy on job creation, is simply an external condition that they can suffer or benefit from. For policy makers, the strategies that company managers make up and their combined effect on ecosystem creation is hardly manageable. So, the company strategies remain an external condition outside the policy makers' full control. It may come as no surprise that such **different actors define performance in completely different ways.**

Secondly, performance indicators need to reflect performance on **different levels of analysis**, be it the performance of a certain process, a company, an ecosystem of companies, or even the performance of an entire society, for example in terms of carbon emissions. To keep things simple, our analysis does not differentiate performance for different actors but, rather, focuses on performance at the level of the complete IVC (involving a network of firms).

For example, AM has had a significant influence on the manufacturing of prosthetics. Traditionally, prosthetics to compensate for missing limbs were very expensive – costs easily amounted to $50 000 (Love, 2014, as cited in Steenhuis and Pretorius, 2017, p. 129). With the help of AM, students were able to produce a prosthetic for a left hand at the cost of $10 (Steenhuis & Pretorius, 2017, p. 129). Not only was the cost reduced dramatically, the prosthetic was also produced by laymen as compared to the traditional prosthetic produced by orthopaedic technicians. In this example, AM had a positive effect at the local level, improving the quality of life of a person at low cost. The radical change in production cost and the required level of education, however, may devaluate the investment of those who have undergone training in this profession. Yet again, general advancements in AM may have positive spillover effects for the economy as whole.

In order to fulfil the requirements stemming from the different types of actors involved and from the different levels of analysis that are relevant, we decided to formulate three key performance indicators: economic, social and strategic impact, each of which will be defined and operationalized in the next section.

2.8 Definition of performance indicators and their operationalization

The key performance indicators, economic, social and strategic impact, were the outcome of an IAMRRI workshop held in Delft in September 2018. The participants were asked to suggest items that should constitute parts of the key performance indicators. Grouping of these suggestions led to the key performance indicators as presented in table 4.

Defining three key performance indicators was not the only possible outcome. One could have opted for more key performance indicators by condensing the suggested items along more dimensions. However, "the division in three main variables makes sense because it pinpoints completely different types of performance. As a society we would like to stimulate all three (win win) yet in practice an increase in the one can also imply a decrease in the other types of performance. If so, the performance indicators need to be balanced and that is a political choice. It is exactly this balancing that requires governments or institutions such as the EU to safeguard the right balance from a societal perspective. Such a balance would most probably not have appeared in a completely free market where specific stakeholder groups dominate at the expense of other stakeholder groups. By nature, competition does not lead towards balance" (Ortt, 2018, p. 7).

Table 4. Definition and operationalization of the key performance indicators

key performance indicator	definition	operationalisation(s)
economic impact	Economic impact is measured in a narrow sense in terms of the number of actors with access to involvement with AM, in terms of customers, market share, in terms of number of products sold from suppliers to customers as well as the resulting turnover and profitability. Economic impact thus focuses on the relevant AM webs of innovation value chains, or the "AM-industrial ecosystem".	installed base, profits generated in the AM ecosystem, market share of AM products, number of new businesses and companies by AM., number of European products/ service/ businesses being unique globally.
social impact	"The performance of the system in more normative and less monetary terms, [studying] the effects of the system on more actors than just suppliers/producers and customers alone. In doing so, stakeholders outside the directly involved actors on the supply and demand side of the market are considered. Considerations important for future generations, or EU-citizens that are not customers but are impacted by the behaviour of supply and demand, are also taken into account. In doing so, not only direct economic monetary indicators are used to study the system but also normative aspects that we consider as important for the society at large, now and in the future" (van de Kaa, Sobota, Ortt, et al., 2019, p. 4).	awareness for AM in the society, positive attitude of customers towards AM products, sustainability, sustainable supply chain models, knowledge on AM across all agents (D3.1, p.33); acceptance and acceptability, number of jobs created by AM (jobs also sound with respect to RRI – gender equality perspective)
strategic impact	"The effect that the relevant AM webs of innovation value chains, or the "AM-industrial ecosystem" has on the EU. Strategic impact, in comparison to economic impact, thus deliberately looks outside the AM industrial ecosystem. Stimulating employment, increasing knowledge intensive and thus high-level activities in the EU, competitiveness vis-a-vis other parts of the world, and effects of the AM webs of innovation value chains on traditional manufacturing activities all represent a kind of strategic impact" (van de Kaa, Sobota, Ortt, et al., 2019, p. 4).	number of technical solutions/products leading to an increase in jobs. number of AM solution leading to an improvement of society and future perspectives, number of EUROPEAN growths, number of AM engineers (academic training), number of solutions for grant European challenges

2.9 Prioritized list of factors and their operationalization per key performance indicator

An initial literature study on factors for the selection of AM innovations led to 168 factors, in terms of economic, social and strategic impact, although with significant overlap and partly excessive level of detail. After consolidation of overlapping factors and removing excessive level of detail, 52 factors remained.

To arrive at the relative importance of these factors with respect to the three key performance indicators, a workshop was organized in which participants were asked to compare the 52 factors in their importance for each of the key performance indicators. This choice was left entirely to the participants, meaning that they chose from the same set of factors for each of the key performance indicators (one and the same factor could have been relevant for each of the key performance indicators). The participants did so in questionnaires based on the Best-Worst-Method (Rezaei, 2015, 2016), which allows for the calculation of relative factor weights, indicating the importance of a factor relative to the other factors. These relative factor weights were used to rank the 52 factors for each of the key performance indicators. Table 5 summarizes the five most important factors per each key performance indicator, based on the relative factor weights, and Appendix 1 summarizes their operationalizations and proposals for their measurement. It is important to note that we established the relative importance per key performance indicator, not across key performance indicators. Further details of this analysis are included in D2.2 (van de Kaa et al. 2019b).

Table 5. Summary of prioritized factors by the industrial partners for each performance indicator. See appendix for operationalization and proposed measurement of each factor.

Economic impact	Social impact	Strategic impact
L1. Imitability, scalability, and integrability	I6. Social norms	N3. Science literacy and scientific education categorisations
A3. Customer need	I3. Public health	E4. Learning orientation
L3. Failure to consider influential factors	I1. Environmental sustainability	B1. Relative technological performance
L2. Failure to consider actors / stakeholders	N3. Science literacy and scientific education categorisations	A3. Customer need
N5. Open access categorisations	N4. Ethics categorisations	G2. Regulator

The result of this part is a conceptual framework which consists of independent variables (the factors; section 3.3) and dependent variables (the performance indicators; section 3.2). Proposals for the operationalization are made above in table 4 (performance indicators) and Appendix (factors), and they will need to be developed further during the next phases of the project, using further data collection.

3. RRI in innovation value chains of additive manufacturing: RRI understanding of the I AMRRI project

3.1 Responsible Research and Innovation – EC approach

Political framework

RRI as a political driven approach aims to align the research and innovation to the values, needs and expectations of the European society (Lund Declaration 200), Rome Declaration 2014). The Lund declaration under the Swedish presidency of the European Union starts with a forward-looking strategic input to STI-policy. "Europe must focus on the Grand Challenges of our time", as the Lund declaration of 8 July 2009 states: an advocacy for European leadership in R&D, for frontier research, and a joint private and public stakeholder-driven approach. The Rome Declaration claims that "Decisions in research and innovation must consider the principles on which the European Union is founded, i.e. the respect of human dignity, freedom, democracy, equality, the rule of law and the respect of human rights, including the rights of persons belonging to minorities."

Historical development

Owen, Pansera (2019) outlined very precise the development of Responsible Innovation (RI) as a scientific (academic) discourse and RRI as a political driven approach, the common roots and the differences formed between them with respect to science and innovation. Emphasis was on how the RI approach can indicate how the European society will look like or be change by emerging technologies and innovation. The original RI framework was transformed by work of Stilgoe et al (2013) to that what is known as dimension of RRI (anticipation, reflexivity, inclusiveness, openness, and responsiveness). RI and RRI are often seen as similar because of common ideas and objectives, but with the H2020 research and innovation program the EC concept of RRI developed in the directions of the 6 keys i.e., open access, gender equality, ethics, science education, public engagement, and governance.

Understanding of RRI in H2020

According to the EC the H2020 is the biggest EU Research and Innovation programme, which is understood as a **financial instrument implementing** the flagship initiative **aimed at securing Europe's global competitiveness**. 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."[2] This implies that societal actors (researchers, citizens, policy makers, business, third sector organisations, etc.) work together during the whole research and innovation process in order to better align both the process and its outcomes with the values, needs and expectations of society.

In practice, RRI is implemented as a strategic approach that includes a multi-actor preceptive and, enables easier access to scientific results (so called RRI-key open access), the take up of gender equality (RRI-key gender equality) and ethics in the research and innovation content and process (RRI-key

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

ethics), and formal and informal science education (RRI-key science education), and involvement of relevant stakeholders and general public (RRI-key public involvement). The EC funded project RRI Tool[3] also found another key which is seen as "governance". Governance[4] is seen as an umbrella term for implementing activities that deals with policies, rules, processes and behaviour that affect the way in which powers are exercised. Within the RRI discussion the governance focuses on how to carry out research and innovation in a responsible way, and it focuses on policies, processes and procedures offering the proper incentives to the responsible output.

These activities "Gender equality, public engagement, science education, ethics, open access, governance" can be called in several names, such as "RRI operational dimensions" or "RRI dimensions" (Banez-Romero , 2017). They are also mentioned as "RRI actions", "RRI thematic elements"[5], or "Policy Agendas"[6.] In this project, we call them "RRI keys" with the implication that we can use them to unlock the RRI openings. We also acknowledge that there are other ways to unlock the RRI openings, for example, to use "RRI process dimensions", i.e. to be "anticipative, inclusive, reflective, adaptive" in research and innovation process (Stilgoe et al., 2013). In the modelling perspective, we are considering using both, as long as they can help create the RRI openings. We do not want to fix our view now especially when we are still in the process of defining "RRI openings". Below is a brief summary of the "RRI keys"

Framework for public supported science and innovation actions:

The I AM RRI project addresses several views, the innovation value chain, the actor´s and that of the innovation network. Many actors and stakeholders are cooperating and interacting in a science and innovation. With the EC framework this science and innovation action is understood as a project which is financed or co-financed by European funds, nationals or regional findings. That can be tenders or a funding project. Other public funded projects are also seen as part of the same level. According to the European competition law not all the stages in an innovation value chain process are allowed to be publicly funded. According to the classification of technology readiness level funding is given for the first phases research/idea generation or part of second phase of idea development. Networked innovation actions do not only have influence on the individual innovation value chain but also often it targets the overall behaviour actors itself. The EC currently monitors the implementation of RRI by institutional change. If it comes to the involvement of stakeholders their actions often target the whole socio-economic system in which innovation take place. In the following considerations are given, how RRI keys influence the different dimensions and interact with the innovation process.

3.2 Key - open access[7]

The open access key of EC funded research and innovation projects has been already implemented in H2020 research program. Objective of open access is to make research findings available without any

[3] https://www.rri-tools.eu/how-to-pa-governance

[4] https://ec.europa.eu/research/swafs/index.cfm?pg=policy&lib=governance

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

[6] https://www.rri-tools.eu

[7] https://ec.europa.eu/programmes/horizon2020/en/h2020-section/open-science-open-access

barriers for readers. Publication should be easily accessible by open repository strategy. Many publishers in engineering already reacted on the trend and offer open access version for scientific papers.

European innovation system gets by open access a source of knowledge, which also means improved circulation and distribution of knowledge. In the beginning, "open" was only seen in getting access to publication. Nowadays the understanding of open access was transformed to giving access to any results or output of funded research and innovation program (publication, data)

The understanding of open access is under development, and will transform further in future. Open access will transform to open science and sees e.g. giving access to infrastructure and also to knowledge and technology transfer by inter-institutional, inter-disciplinary and international collaboration among all actors in research and innovation. Future strategy points in the direction that all possible options for co-creation of knowledge, knowledge sharing or knowledge/technology transfer leading to a more efficient and widely use of results for science and innovation project. Open access follows the idea to increase the probability of getting to innovation by supporting sharing and exchange the explicit and implicit knowledge derived by science. New ways of knowledge sharing are also optional, so introduced industrial partner of the IAMRRI project the idea of knowledge sharing platforms for upcoming technology fields.

Open Science is a key which influences the phases of innovation value chain development and diffusion, and has an effect on separate actors within the innovation value chain also. The following table (table 6) summarizes the most important topics over the phases of innovation value chain evolution.

Table 6: Impact of key open access in the phases of innovation value chain.

idea generation	idea development	diffusion
▪ broadens the knowledge base of idea generation ▪ access to a higher level of knowledge ▪ access to already experience cooperation partners and experts ▪ knowledge on RRI relevant studies and assessments ▪ access to already existing data, reduction of innovation development time ▪ show competence by open publication ▪ knowledge transfer to other organisation like firms	▪ higher knowledge base ▪ access to cooperation partners ▪ RRI assessment ▪ access to already existing data ▪ access to already existing data, reduction of product/idea development time ▪ risk for successful idea/product development by competition with other firms (reduction of time to market)	▪ optional cooperation partners ▪ products orientation socially accepted by previous RRI assessment and studies of the product or service ▪ higher number of globally competitors, reduced market shares

Actors can decide to give open access to publication repositories, data sharing pools or they can adopt open access management strategies.

Table 7: Gives the relation of open access with perspective of the actors

RRI KEYS	measures	actors in innovation value chain	outputs
open access/open science	▪ having an open access/open science strategy ▪ providing staff training on open access/open science and	▪ AM technology company ▪ OEM product design firm ▪ research institution ▪ training organisations/ Education providers	▪ higher knowledge circulation and equitable access to knowledge ▪ better capacity and basis for robust decision making ▪ improved dissemination of product or service by good reputation ▪ finding the best cooperation partners, knowledge transfer by cooperation - co-creation of knowledge ▪ finding targeted customer and end user for products and services
	▪ make communication activities accessible to diverse stakeholders		
	▪ including open innovation principles and practices in the research activities (including co-design, co-engineering, co-creation, user engagement etc.)		
	▪ create open collaboration platforms or communities of practice		

3.3 Key - public engagement[8]

Public engagement (PE) in responsible research and innovation is about co-creating the future with citizens and civil society organisations. As already shown by the literature research (D2.1) innovation understanding is oriented to customer, methods like lead customer or lead user involvement are already know for idea development. Public involvement widens the known innovation approach to social orientation and stakeholder involvement. The view on the innovation idea becomes broader, changes on the society can be seen earlier and possible negative impacts on society can be understood in early stage of innovation process. Public engagement opens the science and innovation process to the public. Public engagement activities are also understood under the democratisation of science and innovation.

Benefits for the science and innovation are seen in the following points

[8] https://ec.europa.eu/programmes/horizon2020/en/h2020-section/public-engagement-responsible-research-and-innovation

- Public engagements ask for a more scientifically literate society. This asks for more science orientation in the society when be involved in innovation and technology consultation. This key has to be seen in strong relation with key science education.
- Public engagement allows different perspectives, anticipation will bring other light to innovation and helps to create social acceptance for new technologies and product generation.

It helps to understand what are more societally relevant and needed research, and lead to more appropriated answers.

The key public engagement asks definitely for the establishment of iterative and inclusive participatory multi-actor dialogues between researchers, policy makers, industry and civil society organisations, NGOs, and citizens in the innovation process. Public engagement in the different stages of innovation will be different processes, because existing knowledge and challenges are different. A drafting view on the future perspective of innovation can give foresights or innovation assessments. Creation of understanding on new developments and research contributes to build up a mutual understanding. Public engagement will help to understand the drawbacks and critical points of innovations under development and enable an adaptive innovation process.

Table 8: Relation of RRI key public engagement on actor perspective

RRI KEYS	measures	actors in innovation value chain	outputs
public engagement	▪ include stakeholders in the definition/setting of the research agenda ▪ encourage co-decision by different stakeholders, including CSOs	▪ AM technology company ▪ knowledge provider: Research institution, training/ education organisations, universities ▪ customers/users ▪ cluster ▪ government ▪ CSOs/society	▪ different perspectives and creativity in research design and results ▪ higher acceptability or research results ▪ facilitating better solution for societal needs ▪ increased legitimacy and social acceptance of research and science centres ▪ more scientific literate and empowered society ▪ more socially relevant and desirable R&I outcomes
	▪ define the level of participation of stakeholders (from consultation to co-decision)	▪ firms: AM technology company, OEM product design firm ▪ knowledge provider: Training organisations/Education providers, universities	
	▪ allocate financial and human resources for public engagement activities	▪ firms AM technology company, OEM product design firm ▪ clusters ▪ knowledge provider: training organisations/education providers, research institution, Universities	
	offer public discussion session on R&I topics (or topics	▪ firms: AM technology company OEM product design firm	

RRI KEYS	measures	actors in innovation value chain	outputs
	of interest for the promoter of the discussion)	▪ research institution, universities	

With respect to the innovation value chain phases the relation between the RRI public engagement can be seen (table 9).

Table 9: Key public engagement in innovation value chain.

idea generation	idea development	diffusion
▪ include other actors of the value chain in the idea generation (including end users, policy makers, investors)-open innovation ▪ include citizens and civil society organisations in the idea generation through co-creation methods ▪ include citizens and civil society organisations in future studies processes (participatory foresight)	▪ establish spaces for deliberation for projects that run collaboratively ▪ engage stakeholders in the project definition ▪ establish spaces for deliberation with CSOs and citizens ▪ request feedback form affected actors (through surveys and other means)	involvement of public new products and new perspectives of application scenarios

3.4 Key -science education

Science education in RRI can be seen manifold:

Science education on a wide societal basis enables a general increase in general knowledge of the society. This is urgently needed for developing an open and forward-thinking society. High level of science education leads to a better knowledge base on new and rapidly developing technologies. Understanding is the key to a fruitful co-creation of future shape in public engagement. Lack of knowledge in change-oriented processes lead to fear and rejection than to a constructive innovation process.

In the knowledge-based economy innovation, which derive from transfer of scientific finding to innovative products or services need a high level of pre-knowledge and hence scientific education. The relation of academic education on innovation potential of EU is included as a key indicator in the European innovation score board.[9] Nations which are European leaders put emphasis on academic education and lifelong learning.

[9] https://ec.europa.eu/growth/industry/innovation/facts-figures/scoreboards_en

Table 10: Relation of RRI key science education on the actors (measures, actors and output is shown)

RRI KEYS	measures	actors in innovation value chain	outputs
science education	employ innovative teaching methods, such as inquiry-based learning, project-based learning, cooperative learning methods, etc.	▪ knowledge provider: universities, training organisations/ education providers, Research institution	▪ making STEM careers attractive to both men and women ▪ supporting citizens in making informed decisions ▪ increased stakeholder awareness that R&I can create solutions affecting their daily lives ▪ higher stakeholder participation in R&I ▪ new offers of studies in AM
	work on real-life challenges or current R&I projects involving STEM topics and ethical and social aspects	▪ firms: AM technology company, OEM product design firm ▪ knowledge provider universities, research institution: training organisations/ Education providers	
	enable learners to play active role in R&I processes		
	use diverse methodologies to engage different stakeholders: science shops, science exhibitions, science-based competition for students, etc.	▪ firms: AM technology company, OEM product design firm ▪ knowledge provider: universities, research institution, training organisations/ education providers ▪ customers/users ▪ government ▪ CSOs	
	establish new studies and training programs	▪ firms ▪ universities ▪ political decision makers, public authorities	
	provide tailored information to specific stakeholder groups and adapt texts/formats according to target groups	▪ firms: AM technology company, OEM product design firm ▪ knowledge provider: Research institution, training organisations/ education providers	

Table 11: Relation of RRI key science education on innovation value chain phases.

idea generation	idea development	diffusion
▪ include youngsters and students in ideation processes through co-creation methods	▪ include youngsters and students in the development process (through teaching/learning factories methodology for instance)	▪ adapt texts/formats according to target groups, ▪ use different outreach channels, including

idea generation	idea development	diffusion
▪ highlight contribution of young searcher ▪ include different stake-holders in the ideation process, adapting the technical content to the stake-holder's science literacy ▪ organize science shops to generate research ideas ▪ motivate young scientist to found a start up		innovative science communication formats ▪ apply findings of new technologies for production

3.5 Key - governance

Governance is defined as a combined term for implementing activities dealing with policies, rules, processes and behaviour that affect the way in which power is exercised. Within the RRI discussion the governance is interested in finding questions how to make research and innovation is carried out in a responsible way, what are policies, processes and procedures offering the proper incentives to the responsible output. Governance instruments can be support for science, innovation and technology policy and strategies, standardisation activities, regulations, targeted funding. Requirements are also existing to the inner organisational structures or processes of organisations and stakeholders in the innovation process. Governance can have multilateral interactions with the other 5 keys and different impact and results on the innovation value chain processes.

On the innovation sytsem very often, a top down process is seen. Typical instruments are rules and regulations (law) on the national or European level, norms and standards on technology and products or even on management systems. funding programs also on regional, national or European level, tax system on national level or European considerations. Public procurement is also seen as instrument for supporting innovation system. All instruments can interact actors or innovation value chain phases as well.

Regulation, laws, standard and norms are common for interfere with in the phase of product or idea development and phase of diffusion/industrialisation. In most cases the give limits for the innovation itself, but is for societal protection. Incentive like funding – which interacts with phases in innovation value chain and tax release – which interacts with actors domain, aim to support science and innovation in first stage or part of idea development phase. Instruments on innovation system are typical instruments of stakeholders like political decision makers, like government or funding agencies. Funding agencies are seen as organisation which are in close cooperation with political decision maker and are responsible for setting up for and managing funding program. They are not involved in law making issues, but often include laws in rules for funding programs.

Governance can also be implemented structural changes and initiate institutional change. Typical structural modifications are implemented processes and responsibilities in an organisation. Standard and norm often cause also institutional changes. With respect to RRI typical institutional change are internal RRI responsible organisation units, e.g. the establishment of ethical panels, or responsibility for gender equality or the implementation of gender equality plan. As already discussed with the value chain process the RRI keys can implemented in the cooperation action and innovation process itself or in the gates. In principle the are more process oriented. Table 12 gives the relation of the RRI key governance and actors/stakeholders within innovation value chains.

Table 12: The RRI key governance and actors/stakeholders within innovation value chains.

RRI KEYS	measures	actors in innovation value chain	outputs
Governance	develop an RRI governance plan	AM technology company OEM product design firm research institution training organisations/ Education providers	▪ integration of all RRI keys in the within the organisations' structures ▪ reduced unintended and unforeseen practices and impacts of R&I ▪ improved multi-stakeholder engagement
	invest resources to make innovations more responsible to societal needs and concerns	AM technology company OEM product design firm research institution training organisations/ Education providers funding agencies/banks government	
	involvement of different stakeholders (management or advisory boards, funding organizations, other teams or colleagues, CSOs) in setting the R&I agenda	AM technology company OEM product design firm research institution training organisations/ Education providers	
	engage stakeholders in the governing board or the advisory council.		
	appointing a staff RRI expert	AM technology company OEM product design firm research institution training organisations/ Education providers funding agencies/banks Insurance firms government	
	RRI-related training for the staff		
	set up incentive systems to implement RRI-related measures		
	create and implement structures that enable stakeholders' engagement	AM technology company OEM product design firm research institution training organisations/ education providers	

Table 13: Relation of RRI keys science education on innovation value chain phases.

idea generation	idea development	diffusion
▪ implementation of processes to check the project idea and research with respect to influence on societal/ethical impact (foresight, assessments)	▪ assessment of RRI quality of product ▪ implement processes and responsibilities for RRI activities which enables the improvement the product according to RRI keys ▪ dialog with stakeholders	▪ laws and regulations ▪ standard and norms ▪ implement processes and responsibilities for RRI at actor and stakeholders

idea generation	idea development	diffusion
▪ implementation of panels for checking RRI quality of ideas ▪ correlation of research funding to RRI actions (incentives) ▪ political dialog with actors and stakeholders on the possible outcome and critical point ▪ implementation of RRI agents at actors	▪ establish standard and norms for new technologies and products ▪ regulations on funding and tax release for RRI related product/idea developments	

3.6 Key - gender equality

Gender Equality is defined as value of the EU, so the European Commission is committed to promoting gender equality in research and innovation (R&I). In addition, the EU has a well-established regulatory framework on gender equality, including binding Directives, which apply widely across the labour market including the research sector.[10] Gender equality should not only be seen as instrument for increasing the number of females in science and innovation. Gender oriented innovation process has also to be in focus of innovation, public engagement asks for balanced engagement of male and female in democratic decision-making processes. Females shall have the opportunities to have access to higher science education as well have the same access to innovations. In AM this is a very important aspect, because future trends show the tendency that patient have to contribute to the costs for individual medical treatments. Latest European studies (Report on equality between women and man in the EU, 2018) show that if the gap between income of women and male will sustain, poverty amongst women will be the consequence in future. Gender equality can be seen from top down but also from bottom up. Regulations can ask or gender equality actions and rules. But also, societal values, need in science and education, aim of offering gender related products can lead to gender equality actions. In key gender equality many measure and instrument are proposed. The following tables show RRI action and measure for the key gender equality on innovation value chain phases and the actors

Table 14: RRI Key gender equality at actors in AM innovation value chain

RRI KEYS	measures	actors in innovation value chain	outputs
Gender equality	having a gender equality plan implemented	• firms: AM technology company, external supplier, OEM product design firm • research/training organisation,	▪ increased diversity in the innovation process ▪ increased scientific quality and social
	having equal salaries guarantees		
	having family friendly work spaces		

[10] https://ec.europa.eu/research/swafs/index.cfm?pg=policy&lib=gender

RRI KEYS	measures	actors in innovation value chain	outputs
	having gender-balanced management positions (gender equality in career options)	knowledge provider: Research institution, Training organisations/ Education providers • clusters	relevance of produced knowledge ▪ increased participation of women in research, improve their careers and achieve gender balance in decision-making ▪ higher number of labour forces ▪ production of goods and services better suited to potential markets ▪ developing technologies that meet the needs of a complex and diverse user group
	having a team dedicated to evaluating gender equality		
	providing gender equality training		
	fostering gender balance in research teams (same number of male and female researcher, and key people)	▪ firms: AM technology company, OEM product design firm ▪ research/training institution ▪ cluster	
	integrating gender dimension in R&I content	▪ **firms**: AM technology company, OEM product design firm ▪ research/training organisation institution ▪ clusters	

In table 15specific aspects of RRI key gender equality in subsequent phases are summarized.

Table 15: RRI key gender equality in phases of innovation value chain.

idea generation	idea generation	diffusion
▪ identify gender stereotypes during ideation process ▪ create a gender-balanced ideation team ▪ analyse different needs, behaviours and attitudes of men and women ▪ consider gender relevance of research topic	▪ consider different needs, behaviours and attitudes of men and women for idea development and product specification ▪ create a gender-balanced development team	▪ gender considered in dissemination activities ▪ Gender dimension in production of production ▪ Gender dimension is accessibility of product and services ▪ create a gender-balanced development team

3.7 Key - ethics[11]

The European Commission sees the integration of ethics in the framework of RRI in the following way:

> For all activities funded by the European Union, ethics is an integral part of research from beginning to end, and ethical compliance is seen as pivotal to achieve real research excellence. Ethics is

[11] https://ec.europa.eu/programmes/horizon2020/node/767

an integral part of research from the beginning to the end. It is only by getting the ethics right that research excellence can be achieved. The ethical orientation is explicitly to highlighted for the

- the involvement of children, patients, vulnerable populations,
- the use of human embryonic stem cells,
- privacy and data protection issues,
- research on animals and non-human primates.

Discussion with industrial partners in the I AM RRI research gave, that they have a wider view on that what ethical is, the 4 topics given on the EC webpage. Various norm and standards give the industrial guidelines for ethical considerations. In the focus of their consideration is often environment sustainable considerations of technologies, impact on working environment and health aspects of employees. Often aspects from “Corporate Social Responsible (CSR)” are also seen as part of ethical thinking. In principle CSR takes up general aspect of RRI.

The IAMRRI proposal also addressed in research work on the RRI keys with respect to the RRI openings to the innovation value chain in AM with focus in science and innovation. The starting of RRI also include the consideration that responsivity is also to contribute to solutions for Grand Challenges of Europe. Unfortunately, that idea was lost, when the EC concept of RRI turned in direction of keys. In the beginning of RRI Schomberg`s (2013) vison of RRI addressed the topic of Grand Challenges and the direction innovation is going in the framework of innovation. Lund Declaration (2009) on of the EC milestone documents also calls for the alignment of science and innovation to “the grand challenges of our time”. Ethical issues have to be considered in science and innovation in the innovation value chain phases as well as on the content related work bases. For additive manufacturing ethical consideration might arrive from aspect of production process (privacy and handling of individual patient’s data in AM production) or general ethical question on AM products like artificial organs. Table 16 gives the characteristic of the RRI key with respect to the institution dimension.

Table 16: RRI key ethics and actors in the innovation value chain (measures, outputs)

RRI KEYS	measures	actors in innovation value chain	outputs
Ethics	promote critical peer review and internal discussion on research integrity throughout the process	▪ firms: AM technology company, OEM product design firm ▪ knowledge provider: Research institution, Training organisations /Education providers ▪ clusters	▪ avoiding research misconduct or market failure ▪ better understanding of potential impacts, risks and interactions ▪ gained credibility and support from other actors by being open, transparent and honest ▪ improved quality by aligning the R&I practice with
	apply established principles of research integrity (data fabrication, falsification, plagiarism or other research misconduct)		
	apply established principles and legislation to research involving children, patients, vulnerable populations; privacy and data protection issues; research on animals and non-human primates.		

RRI KEYS	measures	actors in innovation value chain	outputs
	consider ethical implications of R&I practices in terms of: environmental impacts; human and animal health impacts; local economic and development impacts; social justice; education.		integrity principles and standards ▪ increased ethical engagement with broader dimensions of R&I ▪ solution to grant challenges of Europe in line with societal sound solutions
	participatory ethics-related reflection and decision-making for the R&I practices	▪ firms: AM technology company, OEM product design firm ▪ knowledge provider: Research institution, Training organisations /Education providers ▪ clusters ▪ stakeholder Insurance firms, Customers/users, government, societal representatives CSOs	
	analyse potential harmful impacts on the public or the environment orientation of innovation idea to values of society (environment, human right, protection of nature, freedom, security establish cooperation with ethical panel and exchange knowledge contribution to grant challenges of Europe (e.g. climate change, energy and raw material resources, aging of society)		

Key RRI ethics has also has an effect in subsequent phases in innovation value chain. Table shows these topics.

Table 17: RRI key ethics and relation to phases in the innovation value chain

idea generation	idea development	diffusion
▪ alignment of the practices with the Code of Conduct for Research Integrity ▪ consult external research ethics expert or ethics committee ▪ engage different R&I actors and beneficiaries in the ethics-related reflection	▪ alignment of the practices with the Code of Conduct for Research Integrity ▪ consult external research ethics expert or ethics committee ▪ engage different R&I actors and beneficiaries in the ethics-related reflection ▪ use future studies (such as participatory foresight) to anticipate the benefits and risks of the project	▪ ensure that the outcomes of the innovation process are used responsibly ▪ ensure that your production process is according to social and engineering standards ▪ apply environmentally friendly AM technologies ▪ set up social economic business models

3.8 Implementation of RRI in science and innovation actions in AM

To align both process and outcome of innovation activities to the social needs, RRI can be used as thinking tool for the concept of "Societal Readiness Level" (SRL) [12]. The project New HoRRIizon has offered SRL thinking tool, built based on adopting "a stage-gating inspired processual focus" (see also IAMRRI D2.3), with the hope that it can help us reflect and mature the degree of responsibility in research and innovation activities. Coming from New HoRRIzon – a project a stage gating model is described for innovation (Nielsen et al. (2018) [13]). These considerations show two important effects, that RRI influence level is decreasing with progress of innovation process, while this cause the effect that social acceptance within the innovation process is increased.

Cross-impact and impact analysis of RRI keys actors and innovation value chain phases

Within the I AM RRI project the role of RRI keys and their openings were investigated by the following research actions.

(a) General description of RRI keys their measures on role and output, Analysis of RRI on the innovation value chain process.
(b) Cross-impact assessment of RRI keys, gender equality, ethics, open access, public engagement, science education, and governance.
(c) Impact assessment of RRI keys on the three gates and stages of the innovation value chain process.
(d) Impact assessment of RRI keys on the actors and stakeholder in the AM innovation system.

(a) To understand the interrelation of the RRI keys (defined by the EC) in the AM innovation system cross-impact assessment was carried out. No interrelation was described by value of 0, indirect interrelation was characterised by value 1, and direct interrelation by a value of 3. A detailed description of the method can be found in deliverable D6.2. The results are shown in Figure 3.

[12] https://newhorrizon.eu/societal-readiness-level-thinking-tool/

[13] https://www.thinkingtool.eu/Deliverable_6.1_Final_April%2030_THINKING_TOOL.pdf

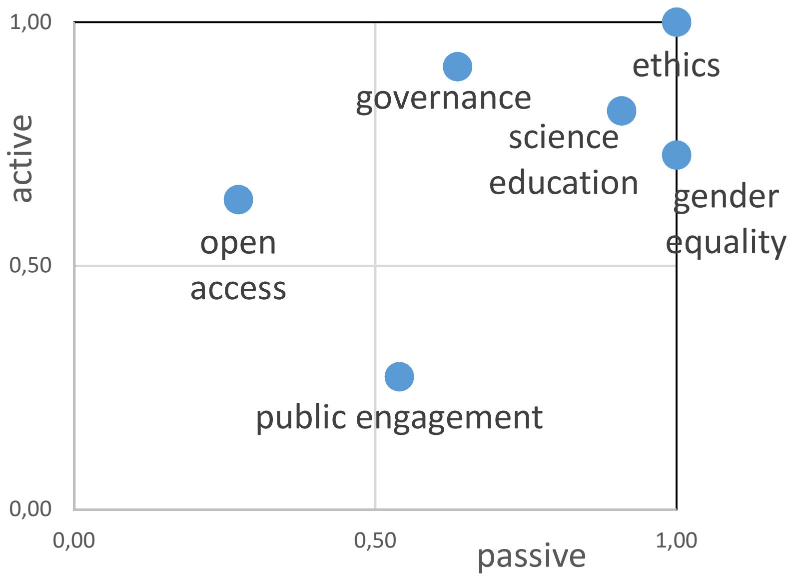

Figure 3: RRI keys cross-impact in AM.

According to the classification given in the IAMRRI deliverable D6.2 (Figure 6) the RRI keys in AM can be understood in the following way.

Table 18: Interpretation of role of RRI keys in the AM innovation system.

type of key	RRI key
strong driver for the AM innovation system	open access
strong cross-linkage: strong interdependency of RRI keys, they are interrelated.	gender equality, ethics, science education, governance
passive factors: can puffer a system	public engagement

From that result it can be seen, that not all keys have the same effect on the AM innovation system. Most RRI keys are not independent, they interrelate. RRI key ethic has the most effect on the AM innovation system. The table show they result of the assessment of cross impact of the RRI key categories. Value of 0 is seen as no interrelation, 1 indirect interrelation and 3 direct relation. It can also be seen that the cross-impact analysis shows a not symmetric matrix, which means some keys have more effect on other categories that they are influenced by them (table 19).

Table 19: Relation of RRI amongst them for AM innovation system

effect of first. column on the other RRI key categories	gender equality	ethics	open access	public engagement	science education	governance
gender equality	hardly any	direct	hardly any	indirect	direct	indirect
ethics	direct	hardly any	indirect	direct	indirect	direct
open access	indirect	indirect	hardly any	indirect	direct	indirect
public engagement	indirect	indirect	hardly any	hardly any	hardly any	indirect
science education	direct	direct	indirect	indirect	hardly any	indirect
governance	direct	direct	indirect	hardly any	direct	hardly any

(b) RRI keys can offer openings in any stage and in any gates of the AM innovation value chains. The impact assessment helps to make it transparent in which stage or gate which type RRI opening will have the highest impact. The evaluation gives inside to the leverage of RRI keys as opening in general but it also shows the potential for openings of the individual keys. Gate 1 is positioned before stage one. At gate on a rough sketch of idea or a project plan of research is known. Gate 2 is after the generation of idea, gate 3 after idea development. From that impact assessment is can be seen that the opening for RRI will be more effective in stage 1 – which is research and idea generation and in gate 2, the transition between phase 1 and phase 2, which is idea development.

Table 20: Type of influence on RRI keys on the phases (also referred as stage) in innovation value chain

RRI Key	idea generation	idea development	diffusion
gender equality	direct	direct	direct
ethics	direct	indirect	direct
open access	direct	indirect	hardly any
public engagement	direct	indirect	hardly any
science education	direct	direct	indirect
governance	indirect	indirect	direct

Tables 20 shows the impact dimension of the keys with respect to the opening potential on the web of innovation value chains (direct, indirect influence of the AM innovation system)

From that it can be interpreted that the implementation of actions deriving from the RRI have the most efficient impact on the AM innovation system in stage research/idea generation. In innovation stage 2 and stage 3 the leverage of RRI keys get less. This in good agreement with the assumption of the NewHoRRIzon project. In addition to the impact analysis it was assessed if stage or gate have different potential to influence the AM innovation system.

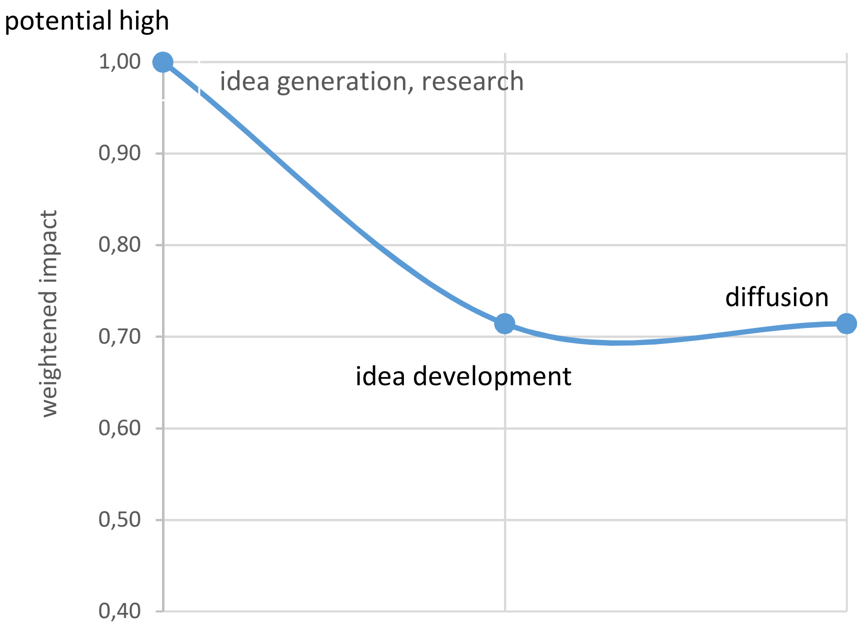

Figure 4: Potential effect of RRI keys in the AM innovation value chain

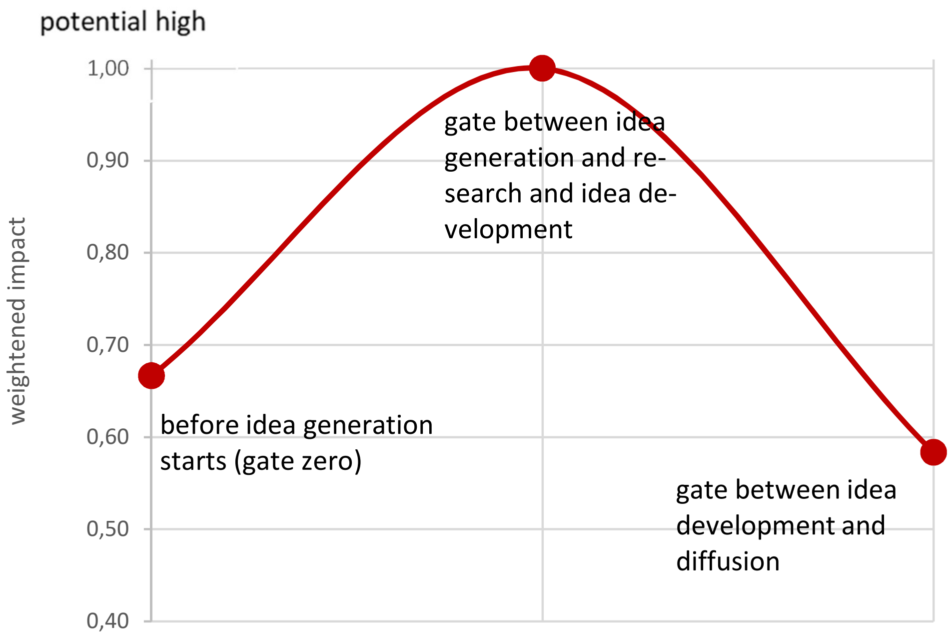

Figure 5: Potential impact of RRI keys on gates between differnent phases in the AM innovation value chain

This analysis reveals a similar result as the matrix before, but it shows that RRI related actions are most efficient in phase 1 (idea generation) and in gate between phase 1 and phase 2 idea development. RRI keys have the lowest effect on the AM innovation system in phase 3 and gate between idea development and diffusion.

The potential for the RRI keys in influencing all phases of AM innovation value chain is given in the next diagram (figure 6). These are governance, public engagement and ethics.

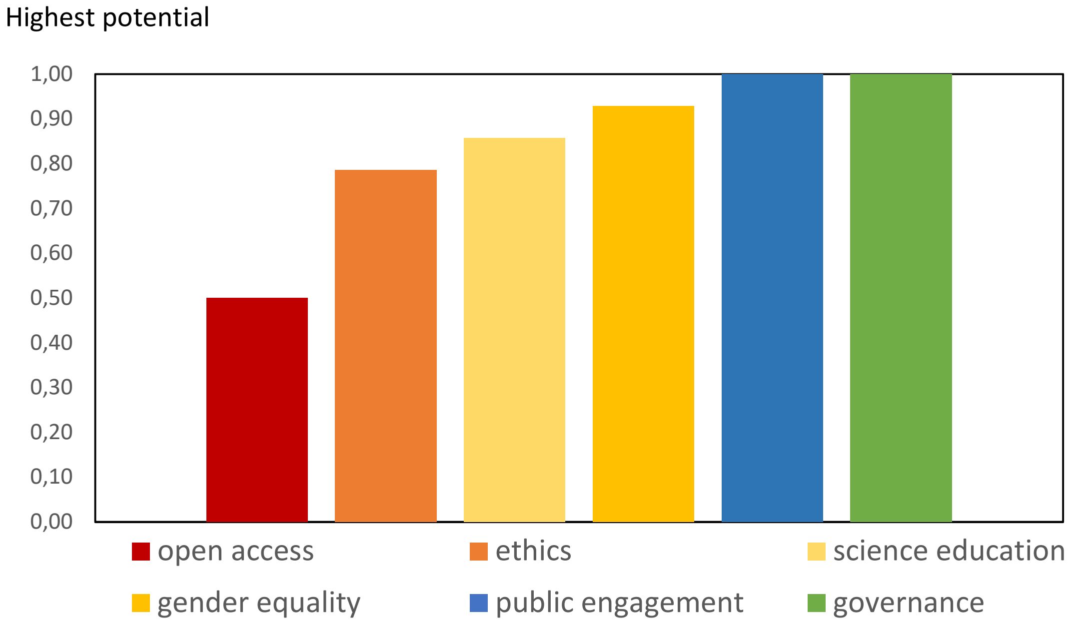

Figure 6: Potential of the RRI keys the actor network in AM innovation system

(c) Effects of RRI keys organisations in the AM innovation system

Organisation take different roles in the AM innovation network, this leads to different potential of RRI keys with respect to pushing towards a social oriented innovation. The first impact analysis was investigation the effect on the different actor organisations. Special attentions were drawn to the different types of stakeholder identified in the actor-stakeholder maps of the AM webs of value chains (D2.3) The result is shown in table 21.

Table 21: How does RRI keys influence actors in the AM innovation system

How does the first column effects on the others?	firms	universities, RTOs	cluster
gender equality	direct	direct	indirect
ethics	indirect	direct	indirect
open access	Hardly any	direct	Hardly any
public engagement	direct	direct	indirect
science education	indirect	direct	indirect
governance	indirect	indirect	direct

Note: Effect are categorised in three groups direct, indirect and hardly any effect.

From that analysis it can be interpreted that university and research organisation are most effected by RRI keys, firms can also be influence by RRI keys, clusters are more effected by governance actions. The next tables show the effect of RRI keys on the behaviour of the stakeholders.

Table 22: How does RRI keys influence stakeholders in the AM innovation system

What is the relation of first column to other columns?	funding agencies	insurance companies	policy makers	standardization organizations	society
gender equality	indirect	indirect	direct	Hardly any	Indirect
ethics	indirect	hardly any	direct	indirect	Indirect
open access	indirect	hardly any	indirect	Indirect	Indirect
public engagement	indirect	hardly any	direct	hardly any	direct
science education	indirect	hardly any	direct	hardly any	direct
governance	indirect	indirect	direct	direct	indirect

Note: Effect are categorised in three groups direct, indirect and hardly any effect.

The table shows that most RRI keys have an effect of the stakeholder as well, but only view have direct impact on the stakeholder. The policy maker and the society are the stakeholder types which has the intensivist relation to the RRI keys. Other stakeholder organisation like insurance companies or standardisation organisation are not seen as strong actors for RRI. It can be considered to leave their role out of the innovation network, if it comes to orientate innovation to social needs.

The potential for the RRI keys in influencing the whole AM innovation network is given in the next diagram.

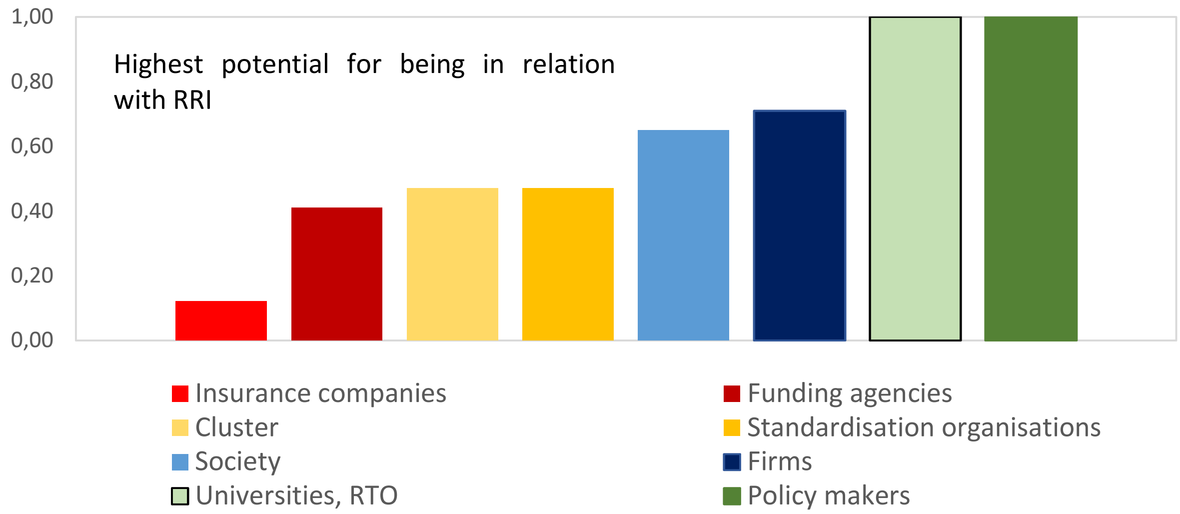

Figure 7: Potentially effected actors or stakeholder by the RRI keys in AM innovation system

The diagram shows that policy maker (government), universities and research organisations, firms and society are the most important actors which have a direct relation to RRI keys. Cluster and standardisation, funding organisation are classified that they have an indirect relation to the RRI keys. Insurance companies have slightest relation to RRI keys.

4. Real-life examples of innovation value chains in additive manufacturing

Real-life examples were collected by interviewing the company and research centre partners of IAMRRI project. The core focus of these examples is to identify the actors involved in specific parts of the web of IVCs in AM and their interactions, to offer input to developing the conceptual model. Also, some input was sought concerning which factors appear as relevant in each specific IVC. Altogether seven experts were interviewed, which resulted in eight different scenarios from where two scenarios were so similar, but from different viewpoints so that these scenarios were combined.

The following sub-sections include narratives of the real-life examples identified in the interviews, together with illustrations of the mapped IVCs. The figures include the following notations:

- Any **actors and stakeholders** are represented in squares.
- The **key actor** in each phase of the IVC is presented with bold font.
- **Information and knowledge exchange and creation between the actors** is coded with blue arrows. These blue knowledge transfer arrows are mainly two-directional, illustrating the feedback loop between the actors who engage in knowledge transfer, sharing and creation concerning the innovation. In rare cases (such as cases with regulations), the blue arrows are single-ended illustrating that the knowledge transfer does not include feedback loops.
- **A key actor's ultimate decision power** over the decision on whether an idea could be developed further and then to be diffused (i.e., act as a decision maker in the innovation value chain) is coded with green arrows.

In the innovation diffusion phase, it is evident that an innovation has some physical deliverables (such as machines, material, software, goods etc.) that flow from actor to actor and this occurs in a manufacturing supply chain. We, however, concentrated on such key actors that need the **knowledge about the innovation,** in order for the innovation to be successfully diffused. It is assumed that if this knowledge transfer and exploitation is successful, then the supply chain can deliver the goods also successfully. Also, it can be noted that the physical products or objects can flow in earlier parts of the innovation value chain as well, but also here the focus is on the knowledge aspect more than the sellable product.

The narratives explain the figures, and also add details concerning the factors relevant for innovation performance in each IVC, as discussed in the interviews. To keep the figures readable, the focus in them is on the actors and their interactions, and the factors are not included in them.

4.1 AM machine development innovation value chain

Starting point for this innovation was that the focal company of this example, namely AM machines manufacturer, had already developed an AM machine for production of ceramic parts, but it needed to be modified to be suitable for manufacturing medical implants. Originally the machine was developed in a triangle relationship with universities (research institute), AM machine manufacturer and dental implant manufacturer (medical device manufacturer). At this point the focus was solely on the AM technology, and aim was to develop the machine to produce ceramics feasibly. The idea came from the research done in the university and dental implants were chosen to be the application area, since it provided a medical ceramics application area without having the issues from certificates and regulatory point of view.

The idea for the actual example innovation came from the customer of AM machine manufacturer which was medical device manufacturer. Medical device manufacturer wanted to start a new business area by producing easily customized implants additively, and they required the machine but no such machine existed yet. Medical devices manufacturer had previously sourced knowledge from regulators and institutions that grant certificates as well as from the insurance companies. The innovation value chain is presented in figure 8.

The existing machine was used as a starting point, but now the regulations had to be taken into considerations. That resulted the development of mainly software and materials, but the hardware as well in a smaller scale. In the idea generation phase AM machine manufacturer was in the central role and sourced information and knowledge from the medical device manufacturer (customer) and from their material, hardware and software suppliers. After several feedback loops this iterative idea generation phase ended when AM machine manufacturer decided to take this idea into development phase.

In the development phase both knowledge and physical objects are exchanged. Firstly, AM machine manufacturers applied for funding from the governmental organization. Material, hardware and software suppliers developed their dedicated products cooperatively with AM machine manufacturer. At this point AM machine manufacturer connected with secondary material supplier to ensure the capabilities to secure the material supply during diffusion. When one cycle of development was done together with the supplier and AM machine manufacturer, prototypes were sent to research institute to be tested. After testing one development cycle was done together with the supplier, then tested again. After test results were good, the AM machine was operated by medical device manufacturer and pilot testing was done together with medical stakeholders. After the AM machine was good enough for the medical implant manufacturer, the decision to finish the product was done cooperatively by AM machine manufacturer and medical implant manufacturer.

In the diffusion phase medical implant manufacturer started their business using this new machine. AM machine manufacturer starts to market their new machine at different fairs, symposiums and conferences. The research institute was agreed to be part of the innovation activities if they can make publications from this innovation process, which also helps the diffusion of the innovation.

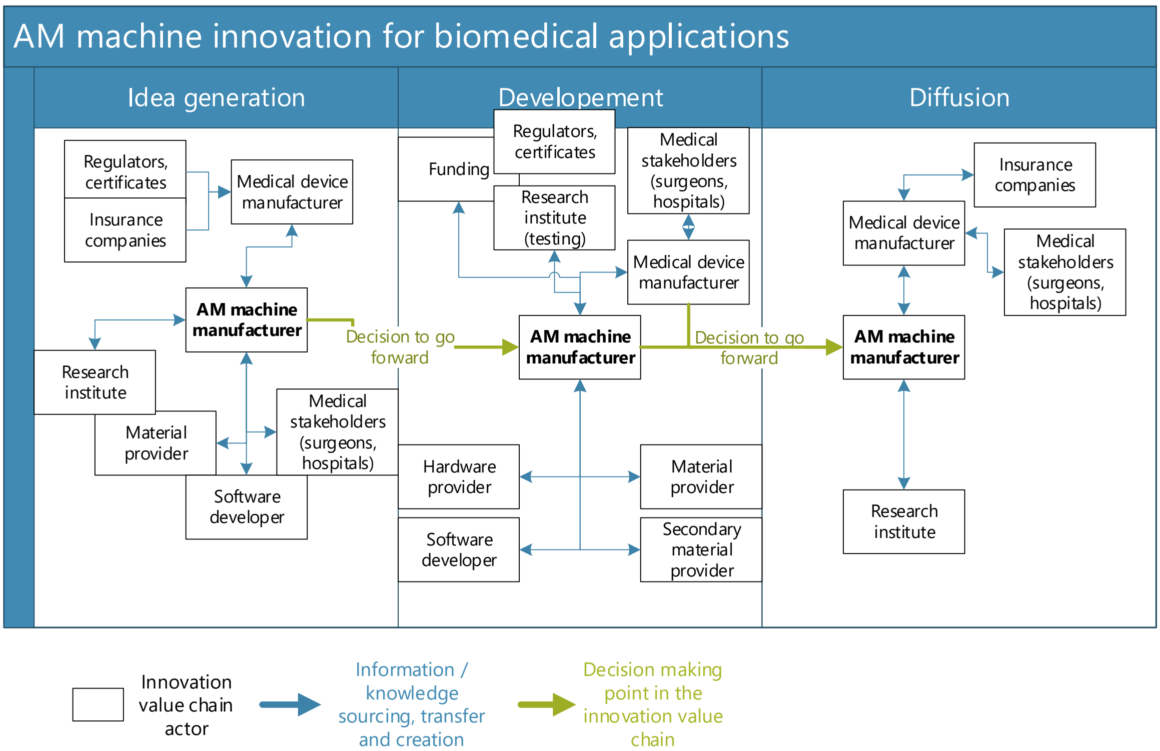

Figure 8. IVC example of AM machine development.

The expert from AM machine manufacturing company identified the following factors, which could explain the success of the innovation: Customer need was high, the technology was a good fit for the customer request, and the innovation was considered to be socially desirable (which for example ensured the external funding).

4.2 AM software development innovation value chain

Starting point of this innovation was that the focal company of this example, namely AM software developer, already has a long history of developing software that are needed to process the 3D-model from CAD-software before entering it into AM machine. AM machine manufacturer had a problem of using the older integration software as it did not provide the quality their customer was expecting. This created a need for new software and AM machine manufacturer asked whether the AM software developer company could solve this.

Figure 9 illustrates the innovation process of AM software development. In the idea generation phase AM machine manufacturer gets a customer request on their machine, that is considered to be a software issue, so this request is passed on to their software supplier (this case's focal company). The idea is then discussed in cooperation between the AM machine manufacturer and AM software developer. After 2-3 weeks of ideating the AM software company decides that the idea is good enough for actual software development to start. In the development phase AM software company developed the first version that was tested by the AM machine manufacturer. After feedback round another version of the software was developed and tested. At this point AM machine manufacturer decided that the software was good enough for their purpose and the diffusion started. The development phase lasted approximately 3 months. The diffusion phase was then quite simply since the new software already had been developed together with the customer of the software (AM machine manufacturer). Now AM machine manufacturer starts to market this as one feature of their machine. Software company also has the rights to market their software to other companies.

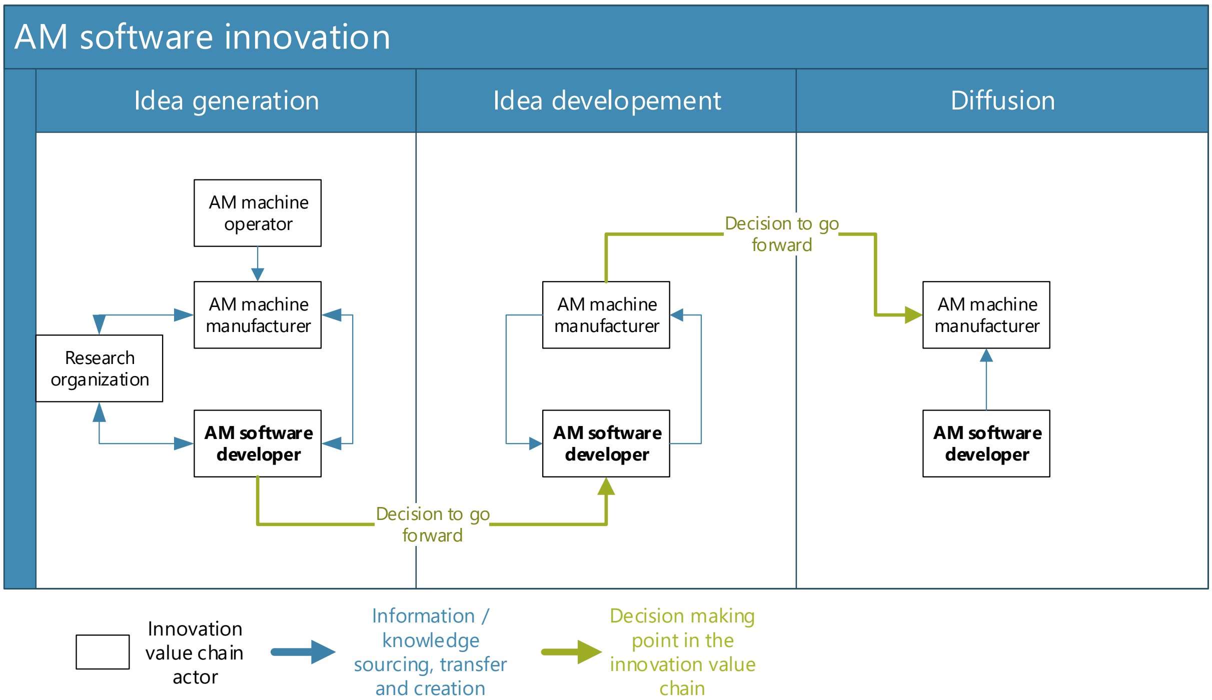

Figure 9. IVC example for AM software development.

From a motivation perspective AM machine wants to produce even better machine and software is important part of it. AM software company on the other hand wants to do business. Engaging into collaborations with the machine manufacturers are considered to be an efficient way to enhance the software business. Factors that explain the success are that there is still a lot of development requirements in the AM technology and the more differed the applications areas become the more accurate technological developments are required.

4.3 AM material development innovation value chain

In this example when the AM material provider started to do material development innovation, they first conduct a thorough market research and use their knowledge and expertise from their customer cases to identify requirements for a new material. This happened internally, but sometimes universities and other research institutes provide new ideas as well. From motivation perspective AM material provider wants to create new materials to enhance their position in the markets. If university gives the idea, their motivation is usually to benefit from the material development and conduct new research out of it. This innovation process is illustrated in the figure 10.

In the innovation development phase the development is done first internally in the AM material company. After having prototypes of the material, it may given for their customer (AM company) to be tested. Another customer company was also involved and those the material properties were given and they were asked to come up with the applications. After the feedback and ideas for applications the decision for a material to be ready do diffused is done by the AM material company. The AM material company then starts to market the material per the ideas they have to what could be the right application area. It is also marketed in the fairs. Also, the customer involved in the developments phase are very good to be directly offered the material.

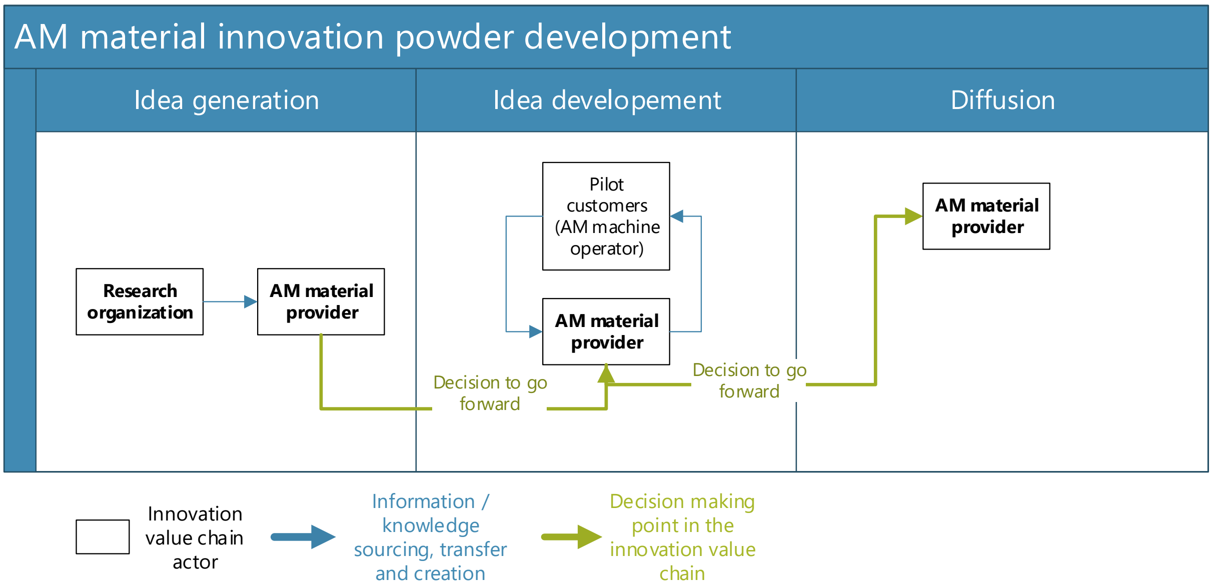

Figure 10. IVC example for AM powder material development.

4.4 AM process innovation value chain, implementing AM machines into production

This example's focal company is AM expert company, that has expertise on AM technology, AM design and they have a good AM network they can provide to solve their customers problems. The example innovation is the AM technology implementation to a company's production process and this company produces lighting devices. This innovation process is illustrated in the figure 11.

The customer, possible implementer of AM, had some previous knowledge about AM and they had the idea that AM could be beneficial to them. They contacted then the AM expert company (AM service provider). The customer wanted to redesign the lighting product and the installation tools. This customer gives the problem specifications information and their requirements are raising the quality and lowering the costs. The AM service provider has the motivation of doing business by solving the customer's problem. Before deciding about the machine implementation to the customer's factory, the AM service producer together with AM designer starts to ideate if they can redesign the product to be produced with AM. After the AM design is considered to fulfil the needs of the customer, the customer decides to proceed to innovation development phase.

At the innovation development phase the AM service provider finalises the product design together with the customer. Then AM service provides utilizes their network of other AM actors by setting up a temporal project organization. AM machine manufacturer is contacted and they provide the suitable machine. AM software provider is contacted and they start the integration of software solutions. AM material supplier is contacted to make the contract of material supply. AM service provider then takes care of the quality assurance and ad-hoc standardization. This project organization then starts the co-operation with the customer's plant engineer and production planner.

After the developed solutions is considered to fulfil the customer's needs, the customer decides to implement the new production system and the manufacturing equipment are delivered to the plant. In the diffusion phase AM service provider ensures that the production starts smoothly. The customer, lighting device manufacturer, then starts to market the new solutions to their customers (engineers and architects)

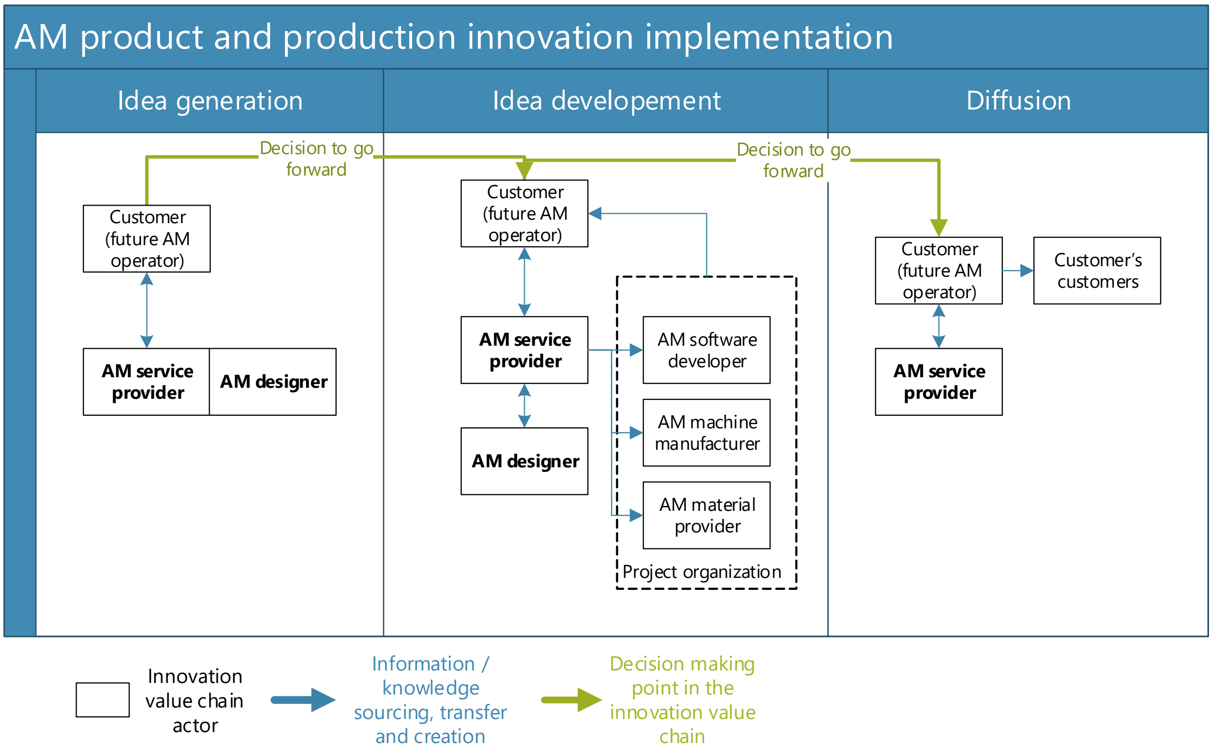

Figure 11. IVC example for AM product and production implementation.

4.5 AM innovation value chains for biomedical instrument

This biomedical application as an example of AM innovations is intended for a surgical instrument. This instrument is used during arthroscopic surgeries. The focal company of this example is AM service provider and designer that is specialized for the innovation idea generation and development. The input for the innovation idea came from the medical device manufacture. Their original instrument's gripper component was 10mm wide and it wanted to be shrunk by 50%. The innovation process is illustrated in figure 12.

During the idea generation phase AM service provider first had iterative process with the medical device manufacturer to get all the necessary information. The AM service provider started stakeholder interviews. These stakeholders were the actual users of the instrument (surgeons) and the technical buyers in the hospital (who make the actual buying decision). Information was gathered from these interviews and after another discussion with medical device manufacturer the decision to move the idea to idea development was done by AM service provider and medical device manufacturer together.

In the idea development phase AM service provider was the central company in this innovation and took care of all the connections to other organizations. The design and first prototypes were done by the AM service provider and that was approved by the medical device manufacturer. Then the design was sent to AM service provider's sub-supplier who will take care of the actual production of the part. Then the manufactured zero series were tested by outside research institute to make sure that the quality and documentation was enough for the certification. After these actions the medical device manufacturer decided that the idea development was ready and the innovated product would be ready for diffusion. In the diffusion part AM service provider withdrew from the project and medical device manufacturer took care of the contracts of the AM contract manufacturer and started to market the product to the technical buyers in hospitals.

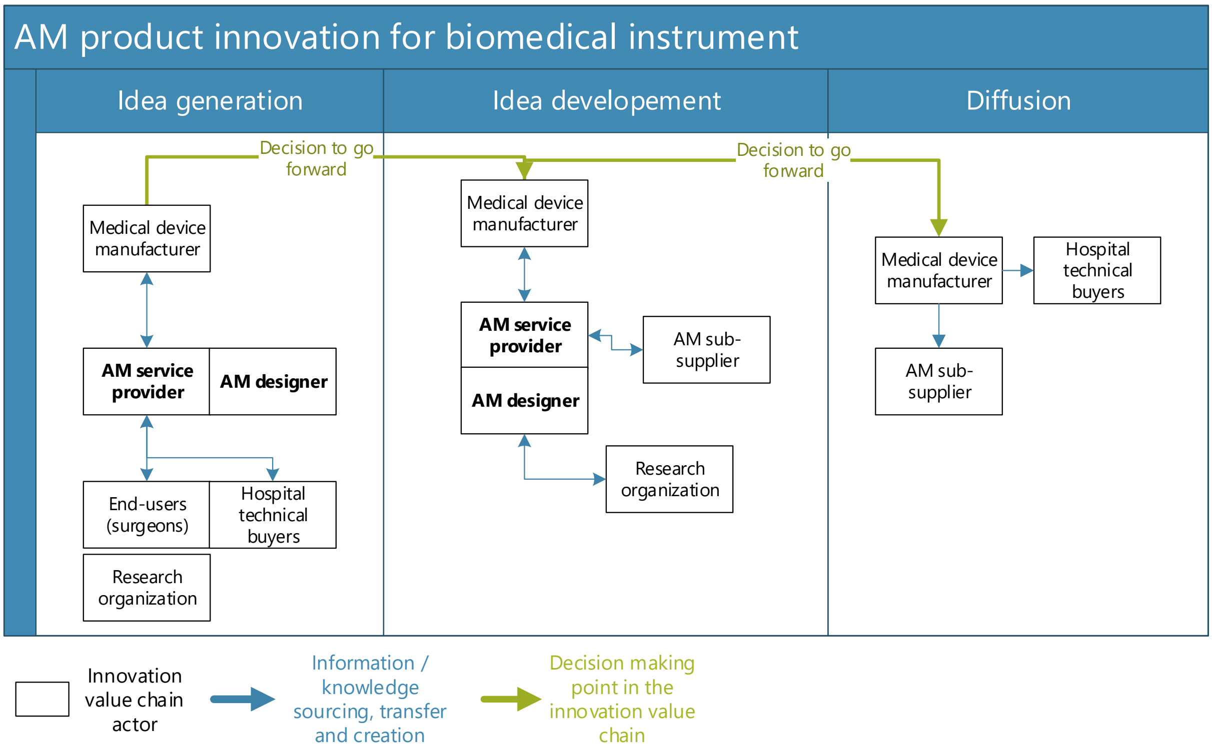

Figure 12. IVC example for developing a biomedical instrument for AM.

The interviewed CEO of the AM service provider company identified the systematic innovation process as the success factor what might explain the innovation success. This means that in the idea generation phase every stakeholder has to be identified (actual users play a big role), comparison to what competitors have to made, and overall make thorough research about the idea (all the involved technology, different version of the idea etc.). Also, during idea development, the possible patents that might be in that special area have to be screened and logistics and distribution channels have to be search in order to make the diffusion phase successful.

4.6 AM innovation value chains for biomedical implant

This biomedical application AM innovation example is an innovation for medical implant. This implant used to replace skull bones when the patient has a decease where parts of the skull's one need to be removed and replaced with implant. Before this innovation that particular surgery was very difficult operation as the skull bones had to be opened, bone removed and replacement implant had to be manually manufactured and fitted to the patient's skull. This resulted a very long and high-risk surgeries. The focal company of this example is the AM service provider and the innovation value chain is presented in figure 13.

In the idea generation phase two different disciplines in the university (medical department and mechanical engineering department) had a discussion if the problem associated with this surgery could be solved using additively manufactured implant that could be designed based on Computer

Tomography picture that could be converted into 3D-model of the patient's skull and from there the bones area needed to be replaced could be isolated and perfect fitting implant could be manufactured prior to surgery. At this point the person from the mechanical engineering department decided that the AM service provider should be part of the project and the idea was then developed in this triangular relationship. Idea generation phase lasted approximately 2 months. After the idea was good enough the medical department of a university decided that the idea should be further developed.

In the development phase AM service provider checked the material properties together with medical department of the university. Prototype parts were then verified in both the university departments who assessed the part. Hospital was involved at this point to provide the first test patient. Medical department with the hospital decided that the implant is good enough for doing the first surgery. After two months of the development the first surgery was done. This surgery was done five years ago and the patient is in good health.

As the first surgery was done basis on an academic research project the larger scale diffusion started after the first successful surgery. Medical academic wrote scientific articles about the subject. The diffusion is however still in process after five years, as it requires time to change the surgical protocols and educate new surgeons and hospital technicians to use this technology. Hospitals have not yet standardized the protocol, making every new operation utilizing this technology a special case where academics have to be involved. AM service provider together with the medical department and hospital try to standardize the procedure so that the medical insurance firms would include this technic as insurance funded method for the surgery.

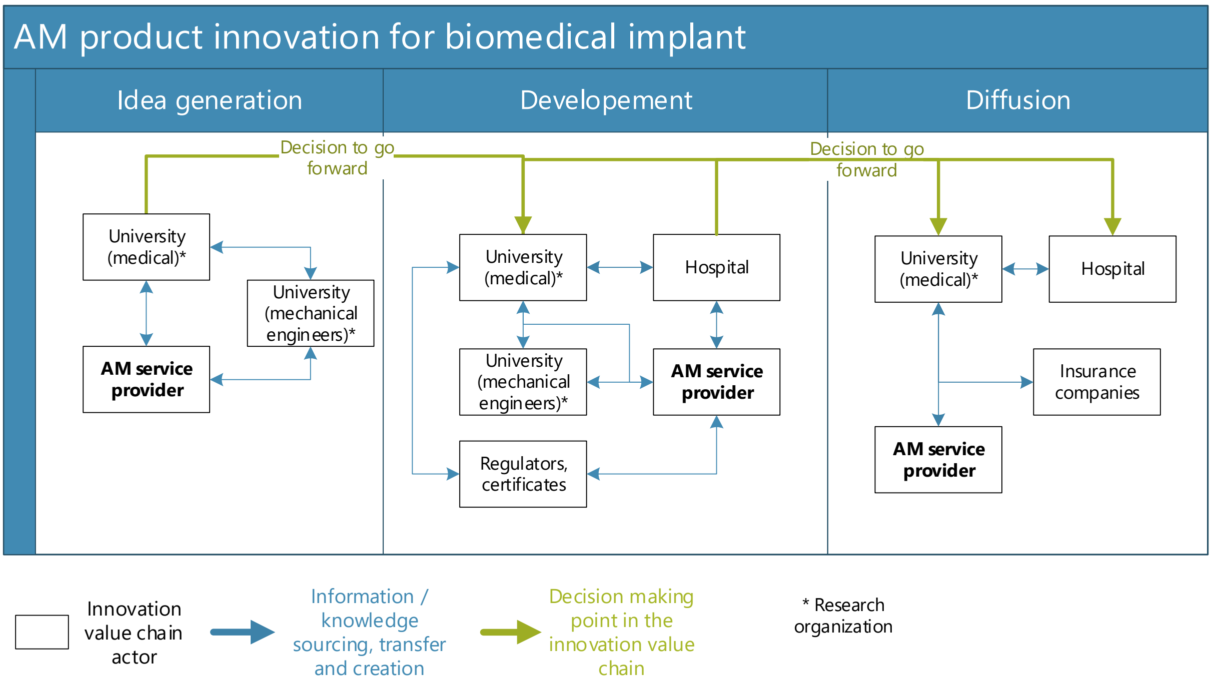

Figure 13. IVC example for AM product for biomedical implant.

The expert interviewed from AM service provider company identified the technological suitability as the factor for this innovation's success. No other technology provides the possibility to manufacture a suitable implant from CT scans. This innovation resulted a starting point for new a field in manufacturing implants additively and utilizing these implants the surgeries. The hospital may now send the CT-scans to AM service providers who provide the implant personalized to the patient.

4.7 Two AM innovations value chains for automotive industry

This innovation value chain example combines two interviews, one expert from AM service provider and one expert from car OEM R&D. The example innovation is a new tool for hot press forming. When the tool is manufactured with AM it is possible to redesign the tool so that the final components are of better quality and the cost is lower than with traditional tools. As this type of AM innovation is the most common one currently a couple of different cases are combined to this example and it is illustrated in figure 14.

The idea may originally come from external supplier for an automotive OEM. They are the tool users and they may have noticed a development need in their tools. Or then the idea may come from the tool manufacturer who wants to serve their customers (external suppliers) with better performing tools. This idea then circulates between AM service provider who considers if this will be a good business case and then they provide the possible solutions to their customer. OEM may be involved at this point or not. In general, the car OEM has the tendency of having a yearly or biyearly meeting with their suppliers where suppliers can present their innovation ideas. From the perspective of AM service providers, they are the one to decide if the idea should be moved into idea development. Of course, their customers also have their saying at this, but usually this decision is made prior AM service providers decision.

During innovation development AM service provider designs and manufactures different prototypes of the tool and sent them to be tested to testing partner and application tester. These partners in this case were the customer, but sometimes they can be different organizations as well. After the customer (External supplier or tool manufacturer) is satisfied they decide that the development has finished and they will start using the new tool.

In the diffusion phase, if the component where the tool is used remains the same but is now better quality, the tool manufacturer starts marketing the tool to external suppliers or the external suppliers start to use the tool. In this case OEM is not necessary to be involved. Trade associations may however be interested in the new tooling device and they might write articles and this way ease the diffusion. If the component is changed (innovation idea from yearly meeting for example) the external supplier has to diffuse the tooling application with the OEM at this stage.

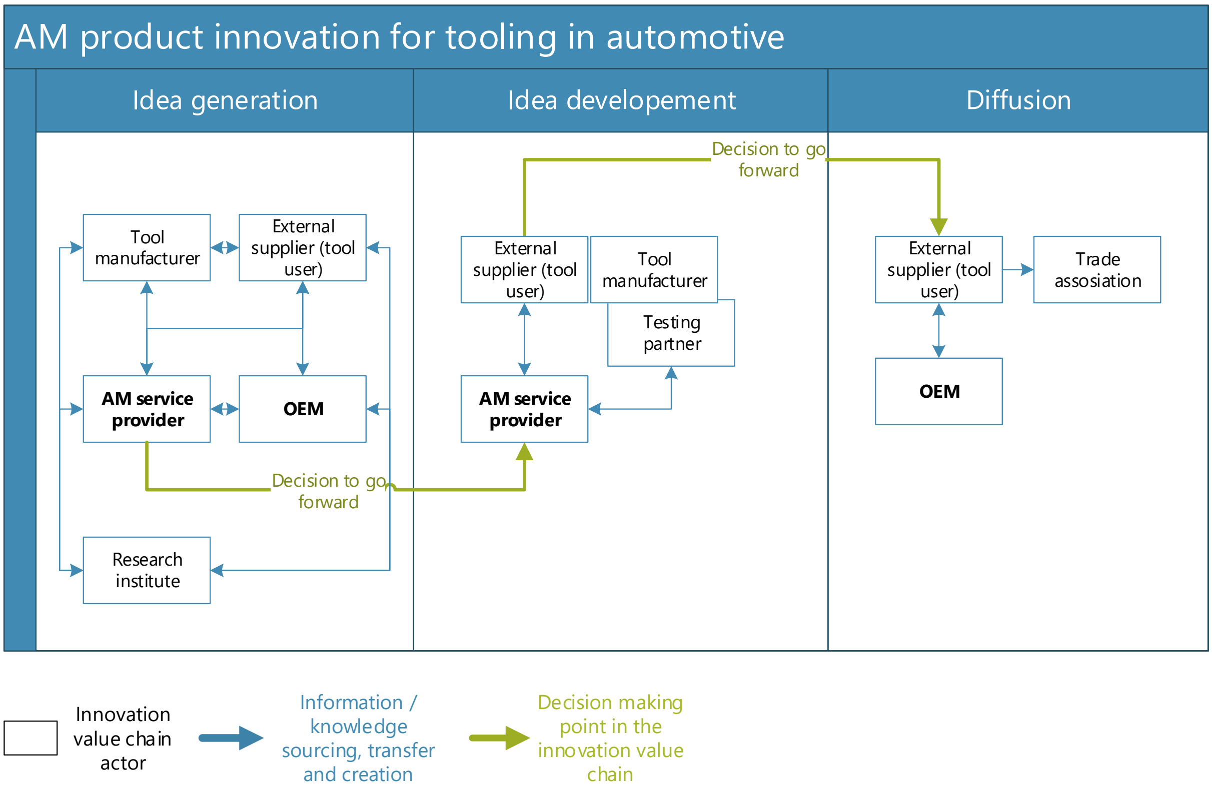

Figure 14. IVC example for AM product for tooling in automotive sector

The innovation process may take time 3 months at shortest and 2 years at longest. Typical time used is around 6 months. If the idea is generated in collaboration with a customer and the solution is based on some previous solution the time is shorter. If there is not a ready-made solution that could be further developed, it takes more time. Also, if research institutes are involved, the innovation has the tendency be quite large and it requires more time. Important factors were identified to be the customer's knowledge about AM, the more the customer knows the more complicated innovation can be developed. Sometimes customer only knows a little and then customer education might be important for the success of the innovation process. Usually small and medium firms of external supplier are more likely to be a good innovation partner, since the batch sizes are usually smaller (where AM is a good fit) than with large supplier.

4.8 Toward webs of innovation value chains

After analysing the real-life examples of AM innovation value chains, we can see some indications that AM innovation value chains are criss-crossing between the different innovation types where AM innovation might occur and operate and between also similar innovation types. Even if the real-life examples represented separate cases of IVCs, they illustrate how an innovation from different or the same level of innovation context may serve as a starting point or as another criss-crossing point for a completely different kind innovation or complementary innovation in the other level. Figure 15 illustrates one possible case of criss-crossing of several IVCs which are fundamental ways of how the Webs of IVCs are emerging.

As the starting point for the example of AM machine innovation for biomedical applications (see chapter 4.1) was a customer need (need from the Medical device manufacturer), we can therefore assume that that particular need from the Medical device manufacturer occurred during AM product innovation for biomedical implants (see chapter 4.6.). Therefore, we can assume that during the development phase of a certain AM implant innovation (IVC 1, in figure 15) the need for a better AM machine acts as a starting point (the idea) for the IVC of AM machine innovation. Already in the ideation phase of the AM machine innovation (IVC 2, in figure 15) the idea generation involves the AM software developer, since software is one of the important technological solutions in the AM machine. Therefore, AM software development (IVC 3, in figure 15) has to go through all the IVC phases, so that the software can be delivered to the second IVC phase of development to the AM machine innovation (IVC 2, in figure 15).

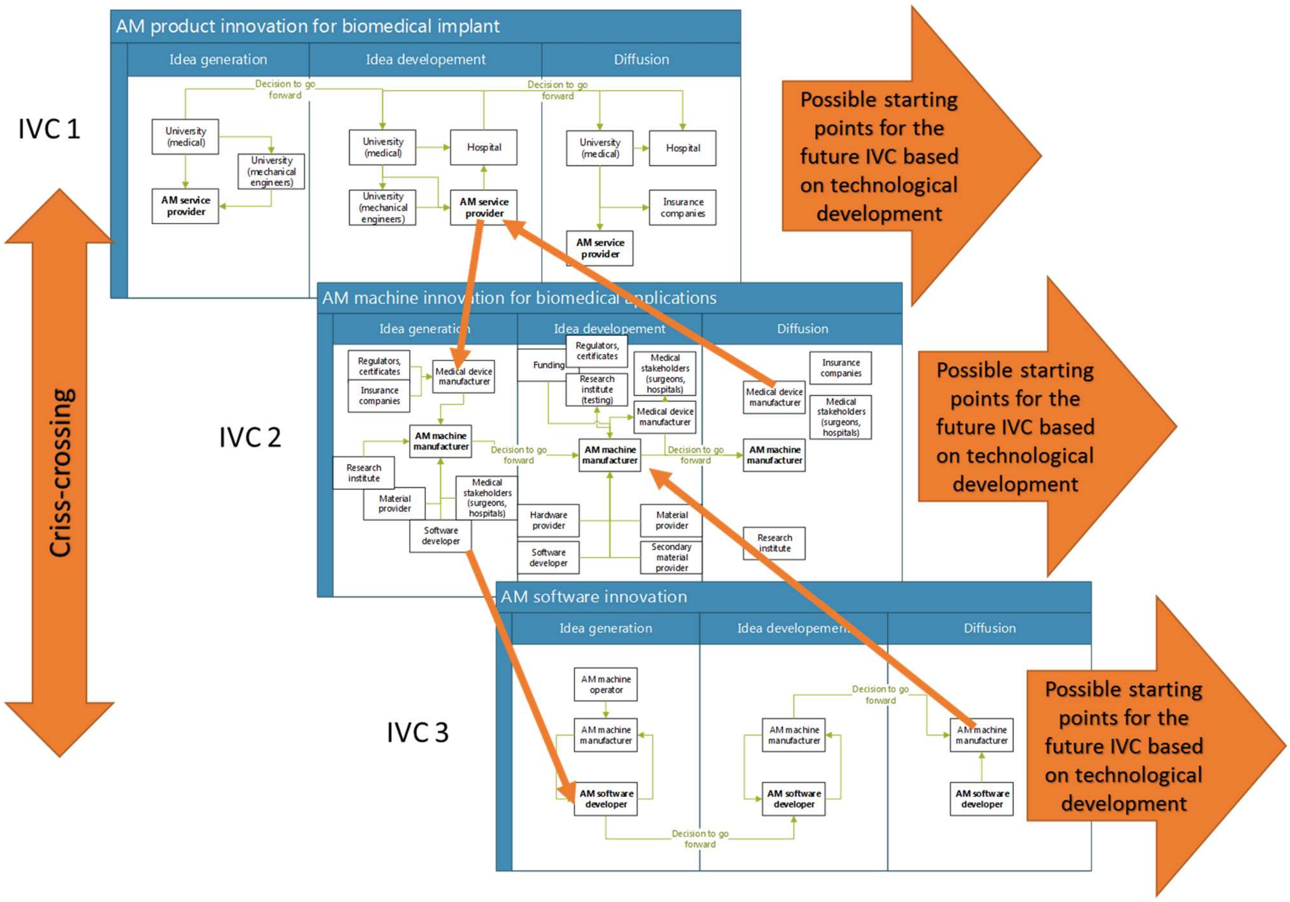

Figure 15. Webs of IVCs example from AM IVCs criss-crossing in the biomedical application sector.

Based on the interview evidence from the AM experts, the previous IVC can also act as starting point for the future innovation. This was the case with IVC 2 in figure 15, where the AM machine innovation was based on earlier AM machine, of which IVC was completely different than the one illustrated in figure 15.

All of the real-life example cases are retrospective and successful. This means that when a case is being observed retrospectively it appears to be linear. This is, however, not the truth and this was noted by many of the interviewees. Innovation process is usually really messy, it involves several feedback loops or restarts and it includes innovation failures, which were not illustrated in the examples.

Also, in real-life cases the extent of the network is highlighted in many cases and it is unlikely that the same kind of a network is active in the following innovations. Starting an innovation means that something new has to have come from somewhere and this newness is forcing (at least in the successful cases) the focal company to source information and knowledge from multiple sources.

5. Conceptual model of performance in webs of AM innovation value chains

This section combines all findings into an overall conceptual model that can be used as a basis for WP3. Before describing that conceptual model, the key results from the previous sections are summarized as entries to the conceptual model. And, we will discuss some issues that are still missing and hence need to be figured out in this section.

5.1 Summary of key results to be included in the conceptual model

In section 2, the performance of an IVC was discussed. An innovation value chain is a network of actors, that together drive the development and diffusion of a specific additive manufacturing technology in a particular market application. Conclusions on the IVC will be further described later on in this section. In section 2, the performance of an innovation value chain was divided in three key performance indicators: economic, social and strategic impact. These key performance indicators are further subdivided to operationalize and measure them in practice. The key performance indicators are influenced by several factors that were described in earlier parts of WP2. It is important to notice that these key performance indicators are reflecting the performance of an entire IVC and hence refer to a network of actors. So, economic impact does not just refer to the profit of one company, for example, but relates to the economic impact of the entire network of actors. The same is true for social impact. These three key performance indicators represent the outcome of the IVCs, the so-called dependent variables. It is important to see how these performance indicators can be balanced and improved for AM technologies.

In section 2, three key issues are addressed, all of which need to enter our overall conceptual model. Firstly, different actor roles in an IVC are described (e.g. AM technology provider and material supplier). For the functioning of the IVC it is important that a complete set of roles is occupied. Secondly, it is important that the actors with complementary roles do cooperate. The cooperation is seen as a type of interaction or exchange between such complementary actors and that can refer to the exchange of information, material and components, for example. Thirdly, a list of RRI openings are formulated (further referred to as the RRI-keys) such as open access and public engagement. These keys do not only refer to societal wishes but may also have a stimulating effect on the speed of acceptance and hence diffusion of a new technology such as AM.

In section 4, the emergence of several different IVCs around specific AM-technologies are described. To track emergence of such IVCs, we distinguished between three generic phases of development and diffusion of an AM-technology in a specific market: the idea generation, the idea development, and diffusion. Seven different real-world cases of AM IVC emergence over these three phases were described. These examples provide an empirical basis for the more general conceptual model.

<u>Issues that still need to be resolved</u>

The generic conceptual model that will be presented in this section 5 will form the basis for WP3. There are three main unresolved issues that are important in such a generic conceptual model. Firstly, we do not exactly know how the IVC typically emerges during subsequent phases of development and diffusion. Where, through which network actor, or through which external factors, is the innovation idea formulated? How does the IVC evolve after such an idea emerged? Secondly, how are economic, social and strategic impact measured of the IVC during subsequent phases of development and diffusion? Thirdly, where are the RRI-openings in the IVC during the subsequent phases of development and diffusion? These issues will be discussed after which we will make well-informed choices and resolve the issues.

5.2 Components and emergence of the AM innovation value chain

The market for additive manufacturing consists of several IVCs, each of which may use different AM technologies to create components or products for different types of applications and different customers. Some innovation value chains are connected, for example when material suppliers or AM machine producers supply material or machines to companies in different markets. Some IVCs are more mature than others, yet this can change over time. The developments in the AM IVCs together represent the emerging market for AM.

The IVC is a key concept in our generic conceptual model. It consists of actors with different roles that cooperate for example through interaction or exchange of information and material. The IVC evolves over subsequent phases of development and diffusion. As explained earlier, three phases are included: idea generation, idea development, and diffusion. In the Table 23 we summarize (1) typical actor roles in AM innovation value chains, (2) types of exchange and (3) phases in AM innovation chain evolution.

Table 23: Key components in the AM innovation value chains.

<table>
<tr><th>different roles (types of actors) in AM innovation value chain</th><th>types of exchange between actors in AM innovation value chain</th></tr>
<tr><td rowspan="3">
• research/education/universities/advice institution
• regulator/standardization institution
• customers of AM components parts or products (usually business customer but can also be consumer household)
• actor designing parts
• actor producing part
• AM machine manufacturing
• AM material supplier
• AM software provider
• insurance firms
• banks/funding agencies
• secondary stakeholders outside the innovation value chain (e.g. general public, public authorities, political decision makers, government), manufacturing companies without AM-technologies, companies outside the WIVC)
</td><td>
• information/knowledge
• material/physical objects
• software/digital models
</td></tr>
<tr><td>phases of development and diffusion of AM-technologies in innovation value chains</td></tr>
<tr><td>
• idea generation
• idea development
• diffusion
</td></tr>
</table>

After emergence of an idea, the idea evolves through the three phases idea generation, idea development and diffusion, but the idea may also be discarded at any point in time during these phases. These phases are a simplification of reality. In practice, if there is no institution that officially demands company networks to follow these phases, these phases may gradually evolve into each other. Later on, we will describe that the EU in order to closely monitor the evolution of AM innovation value chains, may want to distinguish these phases explicitly. We will now discuss the three phases.

5.2.1 **Idea generation**

In the idea generation phase, we found that ideas emerge from widely different actors. In the real-world cases illustrated in section 4 we found that ideas were started respectively by an AM machine manufacturer, an AM software developer, an AM material supplier, an AM service provider, and so on. In our generic conceptual model, we will assume that the idea is generated *randomly* by one of the actors that can be active in the innovation value chain.

In practice multiple actors start cooperating during the idea generation phase by exchanging knowledge and information, but this does not have to be, as was illustrated by case 3 in section 4 in which an AM material supplier generated an idea. In the idea generation phase research institutions can be involved but not necessarily have to.

In the idea generation phase an idea is generated. But what is a complete idea? An idea starts with one or more of the following aspects: new AM material, new AM machine, new product to be created, new AM software, new network of actors that need to cooperate, new (type of) customer, new application of AM products. The first four aspects (AM material, AM machine, product, AM software) represent the technological subsystem of the innovation value chain, the last three aspects (network of actors, customers and formulation of the application of the innovation) represent the business subsystem of the innovation value chain.

The idea generation is ready when the idea covers all of these technological and business aspects and the idea is tested as a working prototype and some benefit or business potential is formulated. So, we assume that idea generation has ended when an idea meets the requirement that it describes all of these relevant aspects and there is a proof of principle and an idea about the benefit or business potential. That means in practice that information and knowledge needs to be actively exchanged between actors and some research is typically performed.

5.2.2 **Idea development**

During idea development the idea (with proof of concept and formulation of benefit or business potential) is developed into an innovation. At the end of idea development, the innovation is ready to be sold or implemented in practice. In other words: the diffusion can start. That means that all technological and business aspects are taken into account and that necessary changes are dealt with. In short all technological and business components required for production and diffusion are in place.

If an innovation is radically new, it may be necessary to create all other necessary components of the technological and business systems anew also. If a completely new material is created, for example, it may be necessary to change the AM machines, the software to design products and that, in turn, may enable the design and production of completely new types of products. Such a change may also require that new actors are involved in the innovation value chain. So, a radically new innovation in one component of the system requires follow-up innovations in other parts of the technological and business systems of the innovation value chain. In contrast, if an innovation is incrementally new, it may be sufficient to use existing components for the other parts of the technological and business system.

In the idea development phase all technological and business aspects to implement an idea, need to be considered. Many complementary actors have to be involved, or their existing technology or role should fit the innovation. In practice the number of actors that cooperate will increase during the development phase. Typically applied research is done in this phase, and market enquiries or tests are scheduled. Most often, research and education institutes are active also. Before actual implementation and use of the innovation it may be mandatory that regulator or standardization institutes have to approve the innovation. During this idea development phase all types of exchange will be visible: exchange of information/knowledge, material/physical objects, and software/digital models.

5.2.3 Diffusion

During diffusion, especially when large-scale diffusion starts, most often the number and type of actors is decreasing again. During the diffusion the innovation value chain may evolve into a market segment. Once the activity in this market segment becomes a standard operation, the actor roles may change.

An important new set of actors, the general public, may become important for the evolution or the growth of the activities in the innovation value chain. During diffusion the general public notices the effect of the innovation in practice. The innovation becomes widely visible and in case of accidents or societal negative side-effects, the public and other outside stakeholders may choose to organize themselves and oppose the consequences of the innovation or suggest fundamental changes to it. This will be more fully discussed below, because Responsible Research and Innovation means that the general public and other relevant stakeholders will be involved during the process of emergence.

5.3 Performance in phases of the AM innovation value chain

Three key performance indicators were distinguished before: economic, social and strategic impact. Can they be assessed during the three subsequent phases of innovation value chain development?

During the phases of idea generation and idea development, potential economic impact, potential social impact and potential strategic impact of the AM innovation can be estimated, but actual performance cannot be assessed in these early phases. In the idea generation and idea development phases, actors can decide to invest in the AM innovation but they do not yet earn money, government can decide to subsidize the development of AM innovations but society does not yet benefit from the innovation. The strategic impact of AM technologies for society can be estimated but is not yet visible in practice. In order to estimate potential performance, some proxies can be used, as indicated in table 24. During the phase of diffusion, economic, social and strategic impact can be actually measured using the operationalizations presented earlier in the WP2.

Table 24: How to estimate or measure key performance indicators during the phases (proxi)

key performance indicator	estimating indicators by using proxies during the idea generation and idea development phase	measuring the indicators during the diffusion phase (proxy)
economic impact	number of companies involved with development of the AM-innovation; Investments in development of AM-innovation.; potential number of new companies and emergence of new industries	installed base, profits, market share, new business and companies;
social impact	awareness of the AM-innovation across relevant actors and general public; attitude towards the AM-innovation by relevant actors and general public; knowledge on AM-innovation across relevant actors and general public.	awareness, attitude, Knowledge; Sustainability of product and supply chain; Acceptance by customers and acceptability by general public.
strategic impact	number of existing manufacturing companies and number of industries potentially impacted by the AM-innovation and new job created. European leadership in AM technologies (IPR)	increase/decrease in jobs increase of patents compared to other global regions

From the table it can be seen that economic and strategic impact can be estimated using several proxies during the early phases of idea generation and idea development. These proxies are different from the indicators that can be measured later on during diffusion. In the case of social impact, however, awareness, attitude and knowledge of relevant actors in the innovation value chain and of the general public can be measured almost from the start. This is an important opening for RRI that will be discussed in more detail below.

5.4 RRI-keys and their effect on economic, social and strategic impact

Six of RRI-keys were formulated:

1. open access (open data, science)
2. public engagement (open and citizen science)
3. ethics (inclusiveness including gender equality)
4. science education
5. governance
6. gender equality

After a workshop with industrial partners, the three most important RRI-keys in the understanding of industrial partner were selected:

1. open access (open data, science) –strong driver key in AM innovation system of AM
2. public engagement (passive key in AM innovation system)

3. ethics (most crosslinked key in the AM innovation system.)

It is important to note that the RRI keys reflect a societal norm in the EU. The societal norm is important because it reflects the way we want to live and work: inclusive, gender-equal and in a an ethical way, working in a transparent and open way, by educating EU inhabitants so they can develop themselves fully while the EU can become an innovative region that benefits from its inhabitants' talents, taking into account stakeholders that may not have the power or ability to defend their interests, and all of this in a sustainable way so future generations can also live and work.

The RRI-keys also have an impact on economic and social impact of AM innovations and thereby strengthen the actual strategic impact. Knowledge of innovations by the general public, for example, is also important for the speed of diffusion of innovations in society. Knowledge may influence the general public's awareness and attitude and thereby increases acceptance and later on adoption of AM-innovations. Aspects such as sustainability, inclusiveness and taking care of stakeholders, will increase societal acceptability of AM-innovations and it may prevent negative side-effects that later on block diffusion and thereby limit economic and social impact. So, RRI keys, if formulated and implemented carefully, may increase social and economic impact and thereby strengthen the EU's strategic impact.

Because these RRI keys have an important effect on social, economic and strategic impact, they also require a careful balancing act. How to balance economic impact versus sustainability (as part of social impact)? How to allow companies the freedom to act in a novel an entrepreneurial way and thereby generate profits while at the same time safeguard the stakeholders in society that are impacted? The exact balance is matter of political decisions. To make well-informed political decisions, it is important to recognize how RRI keys may both positively and negatively influence economic, social and strategic impact (see table 25).

Table 25: The effect of RRI-keys on the three performance indicators

RRI-keys	economic impact	social impact	strategic impact
1. open access (open data, science)	*potential positive effects*		
	open access will speed up development efforts within and across innovation value chains in the EU by sharing relevant knowledge.	open access allows the general public to be introduced to relevant information early on and thereby increase their knowledge.	open access can create a stronger link between innovation value chains and thereby prevent unnecessary double knowledge creation.
	potential negative effects		
	open access will lower the profits of individual actors that generated and developed AM-ideas initially.		open access may cause leakage of knowledge towards other continents.
	potential positive effects		

RRI-keys	economic impact	social impact	strategic impact
2. public engagement (open and citizen science)	public engagement, by including stakeholders early on in the development, is crucial to understand the values that they deem important so these values can be incorporated in the design. This may increase the acceptance and diffusion of AM-innovations later on, and may also lead to new AM-product ideas and designs (Milchram et al, 2018)	public engagement allows the general public to increase knowledge and awareness and form their attitude. This can prevent negative side-effects by signalling such effects early on.	public engagement may increase interest in AM-education programs, increase AM start-up formation, facilitate filling job vacancies,
	potential negative effects		
	Public engagement may slow down the development efforts in the early phases by evoking resistance that can temporarily block development and diffusion.		Public engagement may slow down the development efforts in the early phases because of resistance to change and lack of knwledge
3. ethics	*potential positive effects*		
	Ethics may help balance economic impact with other aspects and thereby prevent barriers to large-scale diffusion later on.	Ethics helps to take into account product and organizational requirements that may later on facilitate large-scale diffusion.	Inclusiveness may increase the workforce and will facilitate fulfilment of job vacancies.
	potential negative effects		
	Ethics may block development and diffusion when demanded yet unrealistic or impossible.		Ethics may block development and diffusion when demanded yet unrealistic or impossible.
4. science education	*potential positive effects*		
	Science and education will increase the innovativeness of the AM-market. Education will strengthen the knowledge of customers and actors in the innovation value chain and thereby increase economic impact in the long run.	Science and education can help to create awareness among students for social aspects of technologies such as AM and will thereby increase social impact in the long run.	Science and education will increase the available workforce, and may stimulate start-up formation.

It is interesting to observe that all of the RRI keys can have both positive and negative effects on economic impact and on strategic impact. In general, social impact is positively influenced by the RRI-keys. If RRI-keys become dogmatic then social impact may be impacted negatively but in general social impact is increased through RRI keys. Science education is the kind of RRI-key that in general has a positive effect on all key performance indicators: economic, social and strategic impact but it requires a long-term investment because its effects are felt after a while.

We deliberately left out governance, also seen as RRI key. We think that the EU can implement various governance mechanisms and adopt several policies that may strengthen the positive effect of RRI-keys on economic, social and strategic impact. Governance will be discussed separately because governance refers to interventions that can be planned.

5.5 RRI keys and openings in the phases of the innovation value chain

The phases of idea generation, idea development and diffusion do not emerge naturally as distinct phases in practice. Idea generation, development and diffusion evolve over time, they may overlap and may emerge without explicit phase beginnings and endings. However, when the EU wants to stimulate the emergence of AM innovation value chains and wants to balance economic and social impact while securing its strategic impact, then an explicit phase division may be useful. In table 26 are the openings in each of the phases to implement RRI-keys by the EU and in table 26 by firms.

Table 26: RRI openings for the EU during subsequent phases of innovation value chains

RRI openings for the EU during idea generation and idea development	
funding by EU for AM-technologies	The EU can stimulate idea generation and development in a pre-competitive way by funding part of the development and web of innovation value chain represented by powerful actor networks: • The EU funding can be aimed at strategic industries and market sectors in which the EU wants to excel (strategic impact). • The EU funding can deliberately request attention for economic and social impact aspects. • The EU can stimulate knowledge exchange between actors within and across innovation value chains by demanding open access for all (partly) funded activities. • The EU can stimulate network formation in innovation value chains by requesting consortia that contain combinations of actor (roles). • The EU can demand early information provision, education and involvement activities to engage the general public. • The EU can demand early concept tests, pilots and market tests when funding the development and diffusion of new AM-technologies.
long-term investments by EU for technology	• The EU can demand a transition towards open access for all of its universities and public research institutes. • The EU can stimulate research and education institutes to make special education and research programs that focus on technology and business aspects for strategic new technologies such as AM-technology.

develop-ment in general	• The EU can stimulate gender equality and inclusiveness by facilitating access of woman and minorities to education and re-schooling activities for strategic new technologies. • The EU can demand technology assessment reports that explore future societal and economic consequences of strategic new technologies.
RRI-openings for the EU during diffusion	
standards, regulation and laws	• The EU can stimulate standard formation by subsidizing committees for strategic technologies. Standards can speed up diffusion of technologies. • The EU can provide tax incentives and subsidies for actors that invest in production and diffusion activities around strategic technologies.

RRI keys can be implemented in different ways: top-down and bottom-up. Top-down implementation by the EU is for example possible by setting requirements for receiving funding, or by direct investments. RRI keys can also be implemented bottom up by individual actors (organizations or companies) for example by actively aiming for gender equality. An organisation with a balanced population of employees, for example, can provide a positive working culture and that may help to attract new talents.

Table 27. RRI openings for organizations during phases of innovation value chains

RRI openings for organizations during subsequent phases	
organisa-tion efforts for RRI	• Organizations can promote open access and sharing of knowledge to foster an open innovation culture and thereby speed up innovation efforts. • Organizations can aim for gender balance by actively seeking for talent in different subgroups. • Organizations can have an ethical culture and thereby create a safe environment that is attractive for employees and potential partners. Ethics also means that organizations take the interests of stakeholders around the company into account, even if they are not potential customers, suppliers or partners. • Organizations can promote public engagement by involving potential customers early on in new product and service development. • Organizations can play an important role in raising knowledge levels of its employees, partners and direct stakeholders, for example regarding strategic technologies. • Organizations can aim for environmental sustainability and in doing so can build up a positive image and increase their business sustainability. • Organizations can aim for a governance structure that reinforces RRI-efforts.

5.6 A generic AM innovation value chain model

After combining all aspects, we can now present a general model indicating how AM innovation value chains evolve over time (figure 16).

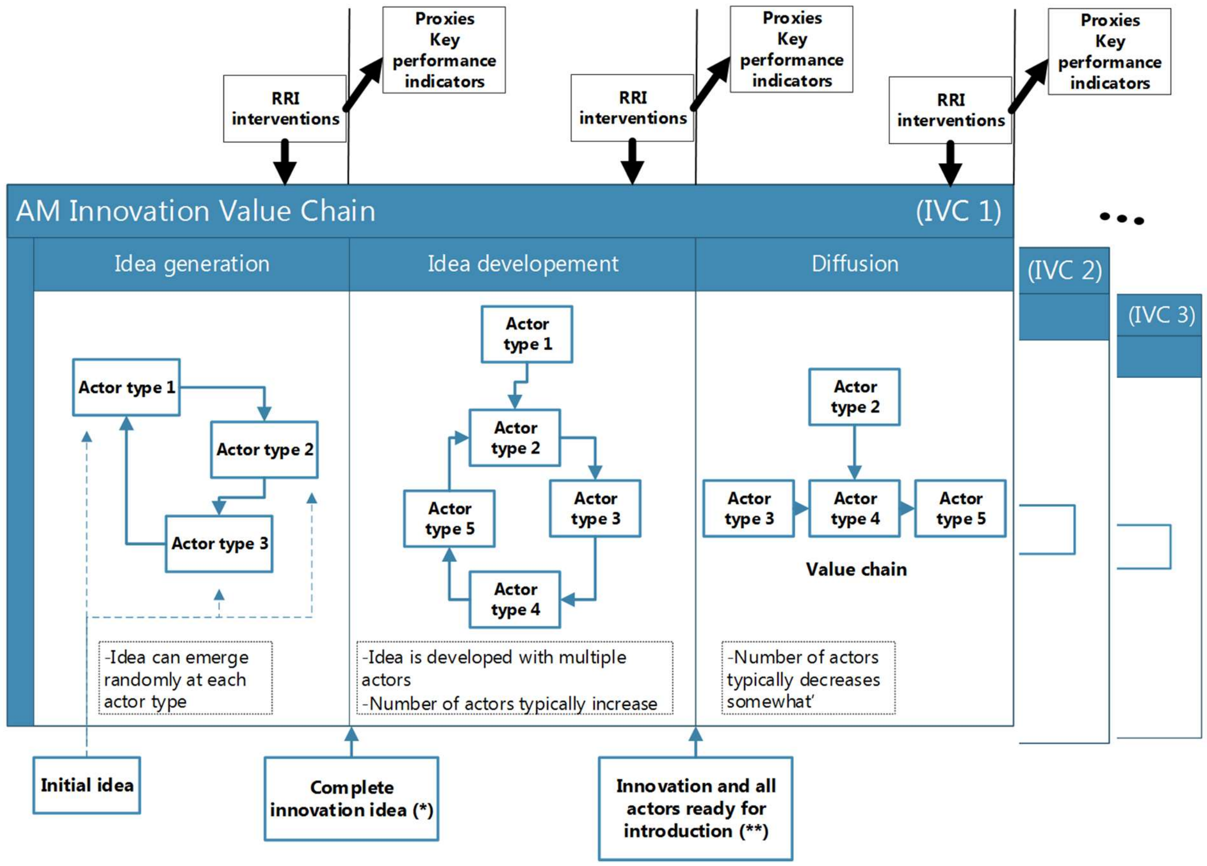

Figure 8: The generic innovation value chain model

Figure notes

An initial idea can start with a description of one technological or business aspect that triggers innovation. This can start in one of the actor types. The technological aspects include aspects such as new AM-material, new AM-machine, new type of product that be created, and new AM-software to create product designs. The business aspects include aspects such as new network of actors that need to cooperate, new (type of) customers, and new application of AM-products.

(*) A complete innovation idea means that there is a proof of principle and that all major technological and business aspects are described (not necessarily implemented) as part of the idea.

(**) An innovation is ready for introduction meaning that all technological and business components required for production and diffusion are in place (implemented) and the innovation can be applied in practice and thus start diffusing.

The actor types refer to the types as described in the text and exhibit on AM innovation value chains. In each phase, actors can emerge or disappear, and the type of exchanges or interactions between actors also evolves over time.

The performance of the entire innovation value chain can be assessed in terms of economic, social and strategic impact. In earlier phases, during idea generation and idea development, proxies can be used to estimate potential future performance.

RRI intervention can be imposed on actors in a top-down way or can emerge bottom-up. In both ways, RRI-interventions will influence the performance of the entire innovation value chain.

In this generic model we distinguish three phases (idea generation, idea development and diffusion. Each of these phases has a starting point (e.g. an initial idea by one of the actors starts the idea generation phase) and an endpoint (e.g. a complete innovation idea marks the end of the idea generation phase). Furthermore, in each phase openings for RRI-interventions can be found either bottom-up by organizations or top-down by the EU. These RRI-interventions have a double effect: they influence the behaviour of actors in each phase and the have an effect on social, economic and strategic impact.

Crisscrossing between Innovation value chains

Market emergence is a complex phenomenon because markets are built up in different innovation value chain simultaneously. Criss-crossing refers to logic linking pins between different innovation value chains. Education and research activities may form such linking pins, and material providers, AM-machine manufacturers and software providers for AM can also occupy such linking positions. The linking pins are important because they prevent double work (innovation value chains can re-use knowledge and components created in other innovation value chains) and increase the speed of development in innovation value chains. Finally, re-using essential components and knowledge across innovation value chains may facilitate compatibility of components across applications.

6. Discussion

The generic conceptual model presented in the previous section is a simplification of reality yet still quite complex. The current section starts to describe the complexity of the phenomenon of market emergence around AM-technologies and the relevance of understanding it anyway. The remainder of the section aims to provide focus before the Agent-Based Modelling (ABM) efforts start in WP3, and it will make all of the simplifications and assumptions explicit. Finally, this section will discuss how to deal with limited information.

6.1 Dealing with complexity

The phenomenon that we aim to explore is highly complex, so agent bases modelling (ABM) is used in next steps to build up understanding. The tricky point is to describe a systems which can be model with the state of the art in AMB.

The phenomenon involves a generic technology, AM, that is in fact a family of related technologies, such as stereolithography and laser /iron powder-bed bonding. AM can be applied using different materials, such as polymers, metals and ceramics. This generic technology can be applied in a wide variety of applications, in many of which different types of organizations (referred to as actors) cooperate and compete in different combinations. Sometimes actors from different markets do cooperate or exchange knowledge and thereby form a linking pin between further disparate markets (we refer to this as crisscrossing). The government represents an important actor in this complex phenomenon of an emerging market around a radically new generic technology. Governments can fund research, can create laws, regulations and stimulate standard setting. Governments can also become a customer when they order AM-manufactured products. Finally, government can stimulate or even force actors to follow specific principles of responsible research and innovation. governments design the environment for the innovation (stakeholder). This complex phenomenon of actor interactions in a playing field with emerging rules can fundamentally change in subsequent stages of technology and product development and diffusion. This very complex system will be modelled to the knowledge of current computational capacities and available ABM models.

With a challenging and complex innovation network, once this modelling is successful let there be no doubt of the relevance of such a model. It will help us to understand the emergence of a new innovations around a radically new technology. This technology can potentially alter the entire structure of our manufacturing industries and thereby change our society in the long term, just like the steam engine and electric power did. Understanding the phenomenon of an emerging market for a generic and important technology such as AM also allows the EU and governments to guide and intervene using various policy instruments. A model that allows experimentation and testing the effect of various policy interventions is an important component in well-informed policy-making process.

In order to cope with the complexity, we suggest a few strategies for AMB modelling. Firstly, we propose to focus our efforts on **relevant parts and technologies of the emerging AM market**. That means we have to deliberately focus on some parts of the phenomenon and leave out other parts. Secondly, we propose to **simplify the mechanisms and relationships between actors and factors**. That means we explicitly suggest some assumptions. These two strategies are a necessary step towards modelling, yet they cannot be made at random. Focus and simplification require a keen eye on the goals and the questions that need to be addressed when building a model. We will outline the basic structure of the model that serves as a starting point for WP3. Such a model will require a lot of data, some of which is uncovered, and some of which is not available.

In the following text we address the following issues:

1. Focus on parts of AM market emergence.
2. Simplifying assumptions.
3. Methodology to deal with limited information.

Focus on parts of AM market emergence.

- Making the model manageable while at the same time covering the main principles requires a keen focus in different ways. We decided to focus our efforts in four directions: (1) the time-interval covered, (2) the submarkets (or applications) addressed, (3) the materials and technologies that are studied, and (4) the level of analysis that we that we considered.

Focus on time-interval

- We start our modelling effort once the AM-developments were taken up by industry, started to professionalize and increase in scope, in practice from the year 2000 onwards. This is when the first professional niche applications started to emerge next to the hobbyists that worked on 3d-printers from the mid-1980s onwards (see remark below)

Focus on submarkets

- We explore only two submarkets of the larger AM-industry: AM in health and automotive. That means we discard markets such as in dentistry, and so on. The reason we opted to focus on these two markets is that they are highly different (heterogeneous) and therefore represent the larger population of possible and actual submarkets.

Focus on material and technologies

- We will focus on ceramics and metals (and discard polymers for example) and we will focus on powdered laser fusion technologies and stereolithography.

Focus on level of analysis

- We will focus on actors as organizations and model how they collaborate or connect in some way and hence form a network. So we do not model parts within organisations, such as individuals, groups and departments in organisations.

<u>Remark on the early beginnings of the AM industry</u>

In the very early stage, from the 1980s onwards, AM emerged in the consumer market. Hobbyists started to build their own AM sets to print things for fun. These so-called lead users, being consumers that build their own products out of a hobby, have been important in stimulating further development. We think they have a considerable effect on later social acceptance of the technology because they have shown the practical use of the technology to many other consumers and some of them professionalized and created hubs where other people can print products of their own wishes. Similar developments of hobbyists can be found in the history of technology during the early days of radio and computers, for example.

6.2 Simplifying assumptions

It is important to be explicit about the simplifications that were implemented in our modelling efforts. These simplifications are made explicit by formulating assumptions. In follow-up modelling activities after the project is completed, it is important to consider these assumptions and to choose which ones to remove or reformulate. In this way the model can be updated later on.

- We distinguish phases in the development and application of a broad technology (in our case: AM technology): the idea generation phase, idea development phase and the diffusion phase.
- We look at interactions of relevant actors and factors during the technology development and diffusion.
- Actors are seen as performing one role. In practice multiple actors can perform one role, or conversely, one actor can perform multiple roles.
- We assume that the idea is generated randomly by one of the actor roles in the innovation value chain.
- We assume that in each phase a kind of result is obtained after which the system can proceed to the next phase. Both performance indicators and the effect of RRI-keys can be measured per phase.
- We define innovation value chains as a minimum set of actors/factors in a market such as health or automotive in a specific stage focusing on one technology.
- We define a technology as the combination of a material + bonding technique.

- We see the AM-industry as a set of (adjacent) innovation value chains that evolve over time and from phase to phase. AM-industry emergence is the results of developments in several innovation value chains in parallel.
- Interaction or exchange between innovation value chains in the form of information or components is possible, especially when organizations function in multiple innovation value chains simultaneously. This phenomenon is referred to as criss-crossing.
- We define RRI-keys and indicate how they relate to economic, social and strategic impact.
- We assume that RRI-keys can emerge from within organizations and can be reinforced by EU and government policy.
-

6.3 Methodology to deal with limited information

In WP3 many specific relationships will be distinguished on the basis of the work in WP2. These relationships need to be tested and validated in terms of direction, size, and types of relationships. The complete set of such information will most probably not be available in the current version of WP2, simply because the full ABM-model is not yet available.

In that case we have a few options to proceed and estimate the type of relationship:

- Do very specific literature research to find data on specific relationships needed for ABM.
- Look at similar relationships in other ABM-models that we found as publicly available.
- Ask partners in industry.
- Assume on the basis of logic reasoning.

Each of these options carry a considerable risk, so we aim to cross-validate findings using multiple approaches. Furthermore, after completing our first idea about a relationship the effect and its realism can be tested. This may serve as a kind of safety valve. For example, if we assume a kind of relationship because it is logical and we estimate the size and direction of effect, then after testing we can find out to what extent the outcomes of the model are sensitive to parameter changes. The higher the sensitivity the more careful we need to be with just assuming and using logic reasoning.

7. Conclusions

This report has explained the logic of certain factors leading to performance implications in AM innovations, as well as the logic with which the IVCs of AM operate. It also describes the understanding of RRI with the I AM RRI project and shows the potential effect on actors and the different phase of innovation value chains in AM. Due to the cross-IVC-linkages shown both conceptually and empirically, the setting of AM is portrayed as an extremely complex system that spans through various supply chains and stakeholders in the society. As previous research and literature cover only partial supply chains and certain example innovations, empirical research is necessary, not only to verify and update the model and convert it to a numerical model, but also to offer evidence on the practice of IVCs in different types of AM innovations.

The first studies on RRI keys and the tentative, first-phase interviews conducted for this report provide rough evidence that the conceptual model is applicable to the real-life context of AM innovations and their IVCs. Interviews also showed how the innovation ideas emerge, what factors explain the success of the innovation process during the IVC, how different IVCs criss-cross and thereby form webs of IVCs.

Further research is needed, to identify actual data for different measures (both factors and performance indicators) in different IVCs and contexts (automotive vs. medical sectors). Also, there is a need to find in-depth knowledge on whether and how the logic of IVCs occurs in practice, in different innovation cases. We need understanding also on whether and how the real-life case examples (scenarios) can be generalized in the whole AM innovation system – to what extent the logic of IVCs differs across different AM innovations. Further evidence is needed to estimate how much variation there is in the compositions of actors per IVC, in the formation of webs of IVCs, and the initiation of new AM innovations.

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9. Appendix 1

Prioritized list of factors and their operationalization

Factors relevant to the performance indicator	Operationalization and definition	Measurement scale / units	Level of analysis
Economic Impact			
L1. Imitability, scalability, and integrability	This factor refers to the ability of business model to be scaled up (van de Kaa, Sobota, Spring, et al., 2019). It's a proof concept that consider how the new product can be integrated to the current system. For instance, a new component in sport car. How flexible the product can be installed? How about the maintenance? does the new product improve the performance? Is there any side effect?	Content analysis necessary	business model
A3. Customer need	This factor refers to the need of the customers to have innovative AM products or service. It can be operationalized by number of ideas coming from customers in a given time; number of customers with a need for AM products or services in a given time; the volume of the customer need in a given time (in terms of the number of product or service requests); or the share of AM-related customer requests of the total product/service requests.	Number of ideas, volume of outstanding orders in monetary terms, number of outstanding orders, number of AM-related requests, share of AM-related requests in the total number of requests	network project
L3. Failure to consider influential factors	It refers to the ability of actors in dealing with uncertainty. It can be operationalised in several questions such as: Has the actor considered SWOT analysis as a part of NPD strategic development? Has the actor performed sociotechnical analysis?	Content analysis necessary	business model
L2. Failure to consider actors / stakeholders	This factor refers to the awareness to key actors such as main supplier, customers and competitors. Several proxies to operationalise this factors are: Number of focus group, market research, etc that have been conducted during new idea development (NPD)	Content analysis necessary	business model
N5. Open access categorisations	Qualitative indicator: To which extent does the R&D process of the product provide accessibility to and ownership of scientific information to society and other stakeholders? To very great extent means that open access policies and support structures for data sharing are in use, the work outcomes are understandable, transparent and accessible, etc.	1=No/Very Little Extent 2=Little Extent 3=Neutral 4=Great Extent 5=Very Great Extent 6=Not applicable	any level

Factors relevant to the performance indicator	Operationalization and definition	Measurement scale / units	Level of analysis
Social impact			
I6. Social norms	Qualitative indicator: To which extent does the R&D of the product comply with the social norms of the European society? No/Very little extent would mean a socially/ethically challenging and controversial product and very great extent would mean large ethical/social acceptance.	1=No/Very Little Extent 2=Little Extent 3=Neutral 4=Great Extent 5=Very Great Extent 6=Not applicable	any level
I3. Public health	Qualitative indicator: To which extent does the R&D of the product benefit the public health of the European society? Very little extent would mean that the product doesn't prevent disease, prolong life and human health on a large scale and very great extent that the product is potentially beneficial for the public health.	1=No/Very Little Extent 2=Little Extent 3=Neutral 4=Great Extent 5=Very Great Extent 6=Not applicable	any level
I1. Environmental sustainability	Qualitative indicator: To which extent does the R&D of the product benefit the Environmental sustainability in Europe? Very great extent would mean that the product and the R&D behind it contribute to the quality of environment on a long-term basis and no extent would mean no influence.	1=No/Very Little Extent 2=Little Extent 3=Neutral 4=Great Extent 5=Very Great Extent 6=Not applicable	any level
N3. Science literacy and scientific education categorisations	Qualitative indicator: To which extent does the R&D of the product promote and improve the science literacy and scientific education in the EU? To very great extend means that the product R&D involves activities that provide citizens with a deeper understanding of science, shape their attitudes towards science, and develop their abilities to contribute to science and science-related policymaking.	1=No/Very Little Extent 2=Little Extent 3=Neutral 4=Great Extent 5=Very Great Extent 6=Not applicable	any level
N4. Ethics categorisations	Qualitative indicator: To which extent is the product R&D complying with the ethics principles? To very great extent means that the product is developed consulting external research ethics experts or ethics committees, acknowledging different values, interests and ideals, checking for long-term and anticipating possible negative side effects, ensuring the integrity of the R&I practices, etc.	1=No/Very Little Extent 2=Little Extent 3=Neutral 4=Great Extent 5=Very Great Extent 6=Not applicable	any level

Factors relevant to the performance indicator	Operationalization and definition	Measurement scale / units	Level of analysis
Strategic Impact			
N3. Science literacy and scientific education categorisations	Qualitative indicator: To which extent does the R&D of the product promote and improve the science literacy and scientific education in the EU? To very great extend means that the product R&D involves activities that provide citizens with a deeper understanding of science, shape their attitudes towards science, and develop their abilities to contribute to science and science-related policymaking.	1=No/Very Little Extent 2=Little Extent 3=Neutral 4=Great Extent 5=Very Great Extent 6=Not applicable	any level
E4. Learning orientation	Refers to the firms' capacity to learn and absorb information. Average R&D intensity; R&D/sales (*Average R&D to sales*) (Lane & Lubatkin, 1998; Srinivasan, Lilien, & Rangaswamy, 2006) or R&D expenditures for a specific company (information may be available through e.g. business week R&D Scoreboard)	RD expenditure over revenues, RD expenditure	firm network
B1. Relative technological performance	Compares the technological performance relative to other alternatives, for example in terms of complexity, reliability, defect rate, geometrical complexity, quality, user friendliness, etc.	Defects per X parts (produced, sold).	network project
A3. Customer need	This factor refers to the need of the customers to have innovative AM products or service. Can be operationalized by number of ideas coming from customers in a given time; number of customers with a need for AM products or services in a given time; the volume of the customer need in a given time (in terms of the number of product or service requests); or the share of AM-related customer requests of the total product/service requests.	Number of AM related customer requests, value of AM related requests, value / number of AM requests relative to overall number of requests	network project
G2. Regulator	A public sector official that specifies laws and regulations in a geographic area – continent, country or region (e.g., government, Lobbying activities, Regulatory backlog such as liability for 3D printed components). Stakeholders' importance can, e.g., be measured by evaluating their urgency, power, and legitimacy. According to Van de Kaa and Greeven (2017), when they have power, urgency, and legitimacy they can considered very important while when they have a combination of two of these they are important. When they have only power, urgency or legimitacy, they are less important and when they have none of these characteristics they are considered non important. This can be evaluated by experts.	Content analysis necessary	network