Different futures for the European innovation system of additive manufacturing and their implication on society

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ABSTRACT

Foresight methodologies offer an excellent approach for discussion a technology on an innovation ecosystems and society level. Foresight brings in various perspectives and puts the thematic focus into a broader context and bridges the challenges with societal needs. This article outlines four different future scenarios for AM and its relation to responsible research and innovation (RRI) and delineates consequences out of these scenarios. Additive manufacturing (AM) refers to a whole bundle of technologies. Software technologies, design technologies, digital twins, material and machine technologies combine to form a high-tech system. These very dynamic developments are an interesting object of investigation for the approach of Responsible Research and Innovation (RRI). There is a strong link to digitalization especially regarding data for construction plans. The innovation phase is characterized by strong interlinkage between data provider, software engineers, AM machine engineers, powder producers. In the IAMRRI EU project innovation value chains were investigated. The IAMRRI project dealt especially with the impact of such technologies on a broader scale. For defining the scope IAMRRI project has worked out future scenarios. The frame for such scenarios is not only the technological capabilities but also the societal, economic, and policy perspectives. The scenarios were developed in stakeholder workshops.

Key words: Foresight; scenario technique; additive manufacturing; responsible research and innovation (RRI).

Introduction

Additive manufacturing (AM) has gained importance in the last decade. AM has many advantages such as directly manufacturing finished component, reduce time to market by accelerating prototyping, shorten supply chain, on-demand manufacturing, or fabricating custom implants, such as hips and prosthetics. These advantages have helped in taking it to the next level of customized functional end use products. The possible applications are manifold including the areas of aerospace, medical, automobiles, etc. AM is closely linked to software and data because of preparing the design and structure information of the component to be printed. Thus, artificial intelligence and machine learning are becoming integral parts of AM growth. The IAMRRI project investigated, described, and modelled the webs of innovations value chains (WIVC) in the sector of AM with openings for responsible research and innovation (RRI). In addition, a foresight study was accomplished for considering the bund of AM technologies in a broader context. The AM technologies were analysed with stakeholders from outside the project and with factors from societal – cultural, technological, economic, ecological, policy, legal, and ethical aspects.

Foresight in combination with stakeholder involvement was applied as an excellent foundation for accomplishing concrete strategies and actions within the AM innovation system and especially within the WIVC in AM. There are various approaches and methodologies for developing future studies for AM such as Delphi study, trend analysis, workshops with experts, or roadmaps. The applied scenario technique approach in IAMRRI needs well-defined groups of participants. At the best, relevant participating stakeholders have the power, the urgency, and the legitimacy (see

Mitchell et al. 1997) to have an impact within the system. In this case of the AM WIVC triple helix actors (actors coming from science & research, from industry & business, and from public authorities) are involved. The applied foresight approach was the scenario technique with triple helix stakeholder involvement. The RRI process dimensions are covered easily by this approach as the foresight process design was given by co-creation of future scenarios with stakeholder involvement, which is diverse & inclusive, anticipative & reflective, open & transparent, and responsive & adaptive to change. The RRI policy agendas or RRI keys, such as ethics, gender equality, public engagement, science education, open access, are analysed and worked out for each scenario and accompanied the foresight process from the beginning.

The scenario process starts with a context analysis. Trends, drivers, all aspects, which affect, boost, enhance and hinder directly or also indirectly the WIVC of AM are analysed and assessed. The outcome of the context analysis is a list of key factors, a foundation for developing future alternatives. The various future shapes let derive consistent scenarios and investigate consequences and wild cards from the developed scenarios. The time horizon for the foresight outcome will be approximately 20 years.

The structure of this article is divided into Introduction, which provides the context and objectives, methodology, results, and conclusion.

Context to Literature

The frame of the IAMRRI scenario development covers a meta level, a systems point of view. There are several future studies in scientific literature. Gebler et al. 2014 investigate the cost-effectiveness and sustainability of AM. AM has a manifold application potential. For instance, there are studies for the application of AM in cultural heritage (Balleti et al. 2017). Considering the various futures of all these different possibilities goes far beyond this report. We focus on AM in general and especially with application potential in automotive and medicine. Bhattachrjya et al. 2014 investigates prospects of AM and discusses perspectives in healthcare, automotive, aerospace, consumer durables, and special consumer products, tools for assembly. Johnston et al. 2018 emphasis on security issues. In long-term, AM will change the value chains, which already starts with the innovation phase (Bromberger & Kelly, 2017). Digital technologies highly impact AM. These two technology approaches interact and promote each other. Riemer et al. 2019 developed three scenarios for Germany in 2025. They talk about “revolution from the niche”, “interlinked digital manufacturing succeeds” and “system providers under increasing pressure”. Gausemeier et al. 2011 describe futures in AM based on scenarios which match technology push and market pull and analyse this with a DELPHI study. Ryan et al. 2017 study the literature about scenarios for supply chains. Caviezel et al. 2017 deals with technological, economic, and ecological issues of AM and illuminates the technologies and experiences regarding possible health effects as well as risks for internal and external security. Trevor et al. 2018 study security implications in AM and summarize them in scenarios. Jiang et al., 2017 for instance, have studied the AM literature and have characterized and prepared the results for conducting a DELPHI study and a DELPHI projection. The IAMRRI scenarios are linked to the studies of Gausemeier et al. 2011, Ryan et al. 2017, Caviezel et al.

2017, Trevor et al. 2018 respectively. Jiang et al 2017 is connected to each of the IAMRRI scenarios from an AM technical aspect.

Methodology

There are different scenario techniques e.g., experts write various narrative future scenarios (Gaßner R.; Steinmüller K., 2018). The scenario development applied here follows the process introduced by Ute von Reibnitz (1992) and others. This highly structured process is combined with a stakeholder co-creation work. The applied procedure for the whole scenario development in IAMRRI can be summarized in the following six steps.

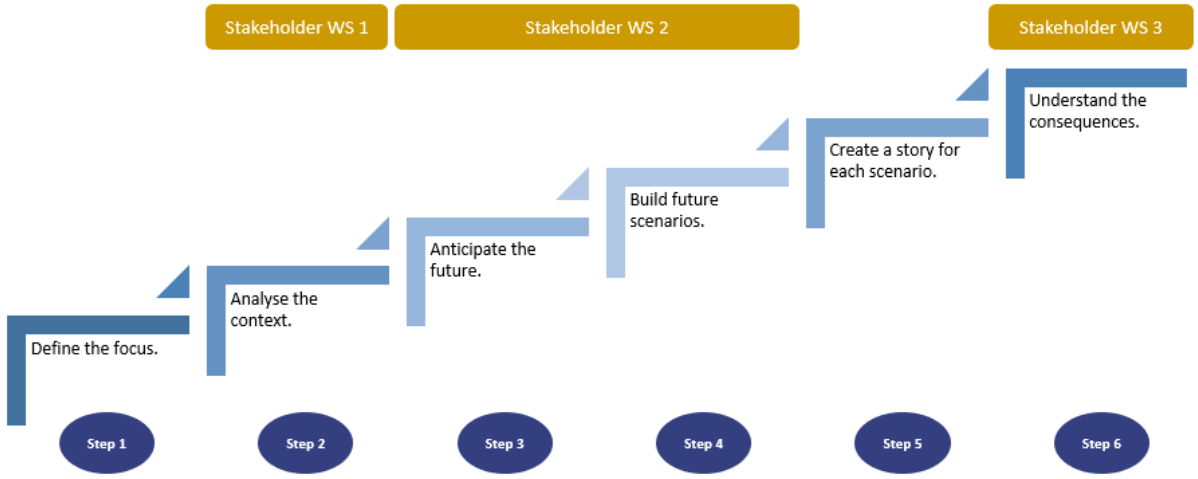

Figure 1: The steps in the applied scenario technique in the IAMRRI foresight.

The starting point, the focus here is the AM innovation value chain and possible openings for responsible research and innovation. AM is a broad field. In this case AM is considered in general with focus on automotive and medical applications. The context analysis is conducted by an analysis of influencing factors structured according to societal, technological, economic, environmental, policy, legal, and ethical aspects (STEEPLE). This assessment of these influencing factors leads to the key factors. Several methods for the assessment of the influencing factors were applied, namely an uncertainty / impact analysis, a cross-impact analysis, and a social network analysis. These methodologies are explained and described in a lot of respective literature.

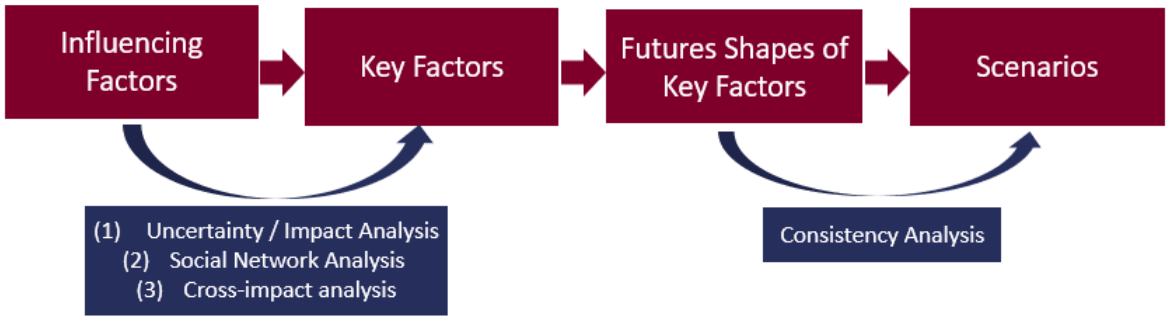

Figure 2: From influencing factors to future scenarios.

For each key factor, however, extreme projections are formulated, which should be as distinct as possible. The timeframe is approximately 20 years ahead. For building future scenarios several methodologies can be implemented to get meaningful and consistent future scenarios. Generally, there is the intuitive holistic way, or there are systematic analytical methodologies. When working with stakeholders we reach for an intuitive holistic approach. A morphological analysis is conducted with all key factors and their future shapes. The bundles of futures shapes, one from each foresight key factor, tells us already the core content of a scenario. The analysis of the consequences in each scenario is the next step. The opportunities and risks in each scenario are discussed. In this case, also the RRI aspects in the innovation process are specifically worked out for each scenario. The three stakeholder workshops took place in the frame of the IAMRRI project. The first workshops were performed in Metz in France with the network of MATERALIA (March 2019), the second in Bilbao with the stakeholder network of TECNALIA (October 2019). And the third workshops took place with the stakeholder network of the Additive Manufacturing Austria platform, online because of COVID restrictions (February 2021).

Results

Each step of the procedure of this approach provides a result, which is the input for the next step. The context analysis presented a list of 56 influencing factors. This list of these 56 influencing factors is described in deliverable D6.2 “Summary of key factors” of the IAMRRI project. The importance-uncertainty rating resulted in 45 factors. The applied cross-impact analysis and a social network analysis together with a stakeholder workshop eventuated in 14 key factors. For each of the 14 key factors different disjoint future shapes were developed. These futures of the key factors provide the foundation of the scenarios, which are built on the consistency of the different future shapes. The details of this outcome are documented in deliverable D6.3 “Report on AM Future Scenarios and Strategies”. In this article puts the work in a scientific context.

Future shapes of the 14 key factors

For each of the foresight key factors two to four different future shapes are developed. The better the different futures of one foresight key factor are described, the better disjoint these future shapes of one and the same foresight key factor, the clearer the different scenarios will be. Some of the boxes are empty. This is because for this key factor no more disjoint future shapes were found.

Table 1: The key factors and their various future shapes.

	Key factor	Future Shape A	Future Shape B	Future Shape C	Future Shape D
1	**Business models**	Products on demand	Responsibility for application		
2	**Effects on other global supply chain**	One step supply chain	Tax disruption	Negative CO_2-footprint	Multicorporate enterprise acting on global level
3	**Regulation**	Very strict regulation all over the world	Lose regulation all over the world	Different regulations regarding strictness and geography	
4	**Education and skills development**	No education and skills needed	Education focused on technical skills	Education focused on creativity	
5	**Trust, reliability, responsibility, sustainability**	"Capitunism" (this means capitalism & communism)	The lucky one always wins (polarisation)	Democratic open societal makers	"Who cares!"
6	**Lobbying activities and strategic market development**	Finished successful lobbying	On-going sustaining lobbying	Contra\backslash (too strong lobby, opposite effect, no support)	Closed down, AM prohibited
7	**Collaboration of different stakeholders**	Customer-centric collaboration (e.g., surgeon)	Artificial Intelligence defines collaboration		
8	**Cultural norms & values (including gender equality)**	Gender equality as a matter of fact	Sustainability and responsibility values	Neo-realism & plutocracy & nationalism (War/unrest)	
9	**Building of critical masses**	Education (existing critical masses)	Niches (no critical masses)		
10	**(Public) Awareness of advantages**	Science faction	Men's domains	Poisoning: Everybody is aware of toxicity and risks of materials for AM	Robot knows
11	**Sufficient maturity of printing technologies**	People-free factory	De-centralized production		
12	**Less usage of resources**	Expensive resources	Cheap resources		
13	**Funding possibilities**	EU top-down funding	EU bottom-up funding		
14	**Open innovation and free transparency of production process**	Mostly open	Mostly closed		

Consistent bundles of futures shapes

There are several methodologies to create meaningful and consistent future scenarios. When working with stakeholders the holistic way seems to be appropriate. For conducting this a morphological analysis supports the work. Each key factor is put on the top. Below the different future shapes of each key factor are posted. The next step is to match the future shapes, which means, take one future shape of each key factor, and combine it to a future shape of the other key

factor. These two future shapes should be consistent. Identifying a bundle of consistent future shapes, where each key factor represented is the basis for the scenarios. The lines (based on the coloured dots) form such bundles. Each of such a bundle leads to a future scenario.

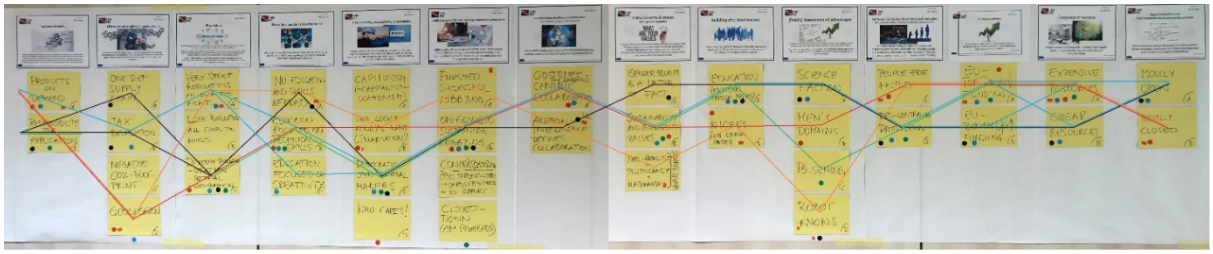

Figure 3. The morphological analysis[1].

IAMRRI future scenarios

Based on the intuitive approach with the morphological analysis the following four future scenarios were identified and described. In the scenario development workshops we work with colours so that we can easier distinguish between the contributions and assign the results to the specific scenario. Therefore, also here the scenarios are marked in corresponding colours.

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

(A) Responsible Europe - sustaining AM system in a well-structured Europe

Sustaining AM system in a well-structured Europe. "Service Provider", consumer purchasing remains in conventional sales channels.

[1] The term morphology comes from antique Greek (morphe) and means shape or form. The general definition of morphology is "the study of form or pattern. (Fritz Zwicky, 1966).

General Morphological Box (analysis) is a method for investigating the totality of relationships contained in multi-dimensional, non-quantifiable problem complexes.

In this scenario the "European" way is continued. In a well-structured world of openness and regulation ethical values, democracy, sustainability, and education are high values within policy and society. Society is built by democratic open societal makers. There are many options to choose for the individuals. Science education becomes more important. Also, public engagement and ethics become more important to individuals.

Education is focused on technical skills, on knowledge and on creativity. It has undergone radical change as it also focuses on creative thinking. AM is also integrated into curricula, and there is an open access system. Society works closely together with engineers. Toolboxes are available for non-technical trained people to solve technical problems. Training of engineers is more holistic and integrates non-technical topics, such as RRI orientation.

Regulations are harmonized and strong. Regulation covers standardisation and legal requirements. They give a secure framework for broad applications of the technology. Some technologies and solutions may disappear due to strict environmental and safety and security regulations. Harmonized regulation worldwide makes global market grow. Ethical values are defined by the society. Ethical panels decide on the framework of these ethical values.

The highly esteemed RRI keys are implemented. Science education, public engagement, and ethics become more important to individuals. There is more open access and more gender equality. Sustainability and responsibility are high values, i.e., waste reduction, and less use of resources as well as circular economy.

There is high awareness in society, so everybody is aware of the risks of AM raw materials and the AM technologies, products. Also, resources are a high valuable good. AM could be a solution with e.g., innovative lightweight solutions and product designs. There is tax on pollution (material, equipment), e.g., taxes for those who will produce waste, and taxes on data.

In this conservative scenario there is only incremental improvement of the AM production system which is mostly open, and user/customer centred. AM is a standard technology used wherever needed. Harmonized and strong regulations give a secure framework for broad applications of the technology.

AM webs of innovation value chain have undergone a consolidation process. AM added webs of value chains and supply chains might be dominated by large global active companies. The monopoly on machine selling, licensed models, licensed designers etc. but the production and innovation process on new products is open for other players, with low barrier access to patents and user-centricity. RRI is reflected in the new products and manufacturing process because ethical aspects, gender, society needs are taken into account. There is still a great variety of possibilities for smaller companies and there is strong knowledge flow but limited by regulation.

AM business models are based on the principle of online ordering and production on demand, which requires know-how on the customer side. Factories are micro-factories, localized where they are needed (neighbourhood, city, etc.). AM production system is decentralized and can be globally.

Consequences for Scenario A "Responsible Europe"

Risks In this scenario regulations are very strong. It could happen that this system is overregulated. Taxes and data tax might not lead to a boost either, every

megabyte might be taxed. This could lead to compulsion on efficiency, but also might inhibit development. AM might therefore remain a niche topic in Europe as it is in the current situation. The innovation power in Europe might be lost especially because of the very strong regulations. Material development, or plant and machine development might be difficult because of the strong regulations and taxes. In case the world outside Europe does not care about responsibility, it would be a big challenge for providing "responsible technology" from Europe to the whole world.

Opportunities Smaller companies (idea generation) might have more opportunities for innovation but might be bought by a big company afterwards. This is due to more flexibility for SMEs.

Innovation might still be implemented by large companies (idea development and idea dissemination). The likelihood for success on the market is higher than for small companies because of their market power.

Standardised materials and equipment might affect higher quality in AM (e.g., Stratasys works).

Regulation such as standardisation might have a positive impact on stable technologies and AM processes, because research organisation, industry, and politics have agreed on a common understanding.

(B) Self-organizing society - AM maker communities and individuals

AM maker communities and individuals "Content Provider", consumer purchasing shifts to online file-sharing repositories.

Differentiation, democracy, individual solutions, and knowledge society are the keywords in this scenario. In this colourful and diverse world individuality is the highest value of all. Individuals share a common understanding of high ethical values. Everybody is responsible for themselves, their education, and their jobs. They have so many possibilities that it is hard to find a "red line". Regulation varies and is not well established everywhere. The innovation and education systems are open and transparent but not harmonized. Education is a good for everybody and a very high value.

Democracy, ethical values, and personal rights are very high values of society. Everyone aims at freedom for themselves and society. Therefore, there are fair social conditions built in a bottom-up way. Sustainability and social welfare and balance are principles on which society and individual decisions are based.

There are no common standards or rules. Regulations are very different regarding their strictness, the sector addressed and the geographical area. Concerning AM there would be a need of regulation and control of what is printed. Also, the taxes which apply tax on material/data and equipment are not harmonized.

The implementation grade of RRI is different based on the geographical area and sector but with a generally high open access to knowledge, innovation, and science education. Gender equality is a matter of fact, there is no loss of talent. Information and knowledge are shared and tools for

collaborative work are common. Sustainability and responsibility are high values, i.e., waste reduction, and less use of resources as well as circular economy. Everybody is aware of the toxicity and risks of AM raw materials.

Government has increased possibilities, but the policy system is more complex. EU funding works bottom-up as there are open calls for all entities with high-risk projects, market and entity driven. Interdisciplinarity is important.

There are many highly innovative specialists and experts. Critical masses on AM are already existing and AM is integrated into curricula. AM education is focused on technical skills.

The AM production system is decentralized as AM products are printed at home or in maker spaces. Everybody has the capability to print at home and his/her own short supply chain. Not the products are sold but the value (e.g., orthoplastic versus warranty). There is a great variety of products. Everybody needs to take responsibility for the whole product life cycle (engineering, dismantling).

The production process is mostly open, with cheaply usable patents, open access to publications. There is great knowledge flow. Open innovation gives a high diversity and easy access to take part in innovation.

Consequences for Scenario B "Self-organizing society"

Risks	High quality might not be guaranteed.
	AM production might require a lot of skills/knowledge for producing a desired and certified product.
	IPRs management might be crucial in this scenario.
Opportunities	Since AM production requires expertise, it might be an opportunity for setting up a good production and business for high-tech AM products.
	Open innovation and open access in this scenario might be great opportunities.
	High acceptance of the technology by the society.
	Since encapsulated safe printing machines are available, the work in maker spaces and at home might offer a lot of possibilities.

(C) Elites of money and knowledge - powerful and mature AM industry

Powerful and mature AM industry "Market Explorer". Use of AM to enhance existing business models.

In this world of geographical and societal imbalances society is dominated by elites who own money and knowledge. Economy is dominated by only a few powerful enterprises. AM is a mature, highly automated, reliable, and efficient technology. RRI principles are tried to be implemented top-down, but they are not of societal interest. There is no gender equality. Only concerning resources, efficiency is a high value due to resource scarcity.

In this scenario society is split and there is a large gap between rich and poor. Most people live in crowded mega-cities in small flats or even around them in slums. They work on the few occasional

jobs that are available. Most of the work is done by machines. Those who live in the countryside earn their modest living working for large farms together with machines.

Most of the people do not have access to higher education so they have no chances to get well paid jobs (poor science education). Only the rich and well-educated elites have the possibilities to provide higher education to their children. Their job is the development and control of machines. They have a very good life which is well-assisted by robots. Those who have the luck to get a good job in a position where humans are still needed, e.g., in creative positions work day and night, to be able to survive and earn the money they need and keep their jobs.

RRI principles are not implemented. There is no gender equality. Science education is underrepresented. Only concerning resources, efficiency is a high value due to resource scarcity.

Regulations are very different regarding their strictness, the sector addressed and the geographical area. Regulation is not harmonized at all. Big markets protect each other (US, Europe, Asia). The global market could fall apart into different protected markets.

EU funding functions top-down, in mission-oriented calls (TRL, segment, etc.) with medium-low risk. Big enterprises have the power to get funding, small players have no chance to be part of the WIVC. Public is not engaged in the innovation process at all.

AM Economy, AM value chains, and supply chains are dominated by only a few powerful organisations having the monopoly on machine selling, licensed models, licensed designers etc. AM is a mature, highly automated, and reliable technology. In the people-free factories no human input is needed for the manufacturing process because the technology is completely mature. Additive manufacturing is a standard technology for the wealthy society. It cannot be used by the masses as they do not have the financial, technological and know-how recourses. AM plants are in all places of the globe for producing the products needed there. These plants belong, of course, to the elites.

Innovation is mostly closed with stronger patent protection, proprietary standards, strong national interests, higher specialization, and efficiency.

AM education is focused on technical skills. The education system is like the status quo (today). It focuses primarily on technical skills rather than on knowledge and science education. STEM degrees are the most popular. Companies are full of highly specialized technicians. It is hard to find these profiles due to high demands, but the job options are limited.

Resources are exploited and therefore already rather expensive. AM could be a solution with e.g., innovative lightweight materials. The use of AM could help to preserve resources and support sustainability and responsibility which are not high values everywhere. AM players are aware of the risks of the material and technologies e.g., toxicity of some AM materials.

Consequences for Scenario C "Elites of money and knowledge"

Risks

Basically, this is an anti-innovation scenario. The elites earn and optimise their money. Innovations might happen only when pressure comes to the system like scarce resources forcing the elites to innovate to keep their financial advantage. For the "normal population" there is hardly any access to resources.

Here there is the risks of monopoly from a few actors (software, material, and

machine providers). The monopoly situation induces also risks regarding agreement between material and machine providers, licence, etc.

AM has a risk to follow "older" industry regarding the gender equality imbalance if no specific action is done. AM can remain a tech for advanced countries and companies. AM components can remain for advanced and developed products for "elite" people. Some might think that "from low-tech to high-tech" and especially from the simple idea "in a garage" to production for the "globe" is only possible with a lot of money. However, in this scenario, the path of success created with little money will not be possible, because the elites will not allow it or buy it up.

Opportunities There will be shadow economy with AM within the poor population. However, this is also an opportunity for ingenious ideas in the low- and high-tech sector (ideas of business and technologies "out of the garage"). Really important is only that the product, the machine, and the process are ready for the market. However, some centralized major actors could simplify the value chain and rule the normative aspect of the market. A decentralization of the manufacturing system is likely to happen with the democratisation of this mean of production (1000 people build 1 product instead of 1 factory building 1000 products).

AM can develop low-budget production, high quality production with a low-budget equipment. It can also have an influence on the education system. Since RRI is implemented more and more woman will work in R&D departments.

This scenario has also implemented artificial intelligent technologies and therefore, AM would have a good chance because AM is very digitalised and thus plays into the hands of robotics developments and AI. AI algorithms might develop AM further.

(D) Robots' world - Artificial Intelligence

Artificial Intelligence serves the world "Mass Customizer". Use of AM to create new business models.

In this scenario the world consists of smart systems everywhere. Artificial intelligence (AI) and robots replace human beings in the production process. The machines serve all humans for wealth and prosperity. Humans have more spare time as the machines do all the hard work. Data on humans is collected and used by AI, and consumption is steered.

RRI is part of the algorithm. Which RRI aspects are programmed into the AI and robots is defined by the people with force. However, the general education level is high. The machines and robots work for the human's wealth and prosperity. There are scepsis about implementing differentiated ethical values. It might not be possible to develop algorithm for a differentiated and broad ethical framework.

The system depends totally on the role of the state and its policies which define how the daily lives of the masses look like. With a strict regulation and high awareness of the system and its dynamics, AI and robots provide standardised wealthy and healthy lives for human mankind. The basis of

wellbeing and peace for humans in this system is secured to a reasonable extent. (Higher/academic) education system and an unconditional basic income are available to everyone. AM products are mass customized.

The houses are smart homes where e.g., the refrigerator is able to refill itself, and a lot of daily life products are identified as being able to be delivered by AM technology immediately and regionally either to your own houses or ordered and produced on demand at AM manufacturing sites. All paths and actions of humans are traced digitally, so huge amounts of data are produced which represent the daily needs, the decisions taken, and the values shared. As data is collected Artificial Intelligence algorithms use it to rule/control our world in a hidden way, thus consumption is steered by AI systems. All areas of life are controlled by AI, medical services, car driving, shopping, et. It is essential who controls the algorithms as society and the distribution of money and wealth depends on the definition of algorithms.

An unconditional basic income for everyone is a profound basis for wealth and peace in this system and is possible because of the efficient and responsible application of technologies for the wealth of humans. Therefore, humans have more spare time and most of us a good life as the machines do all the hard work. However, human decisions are controlled by the AI system providing an environment that uses the data on us and steers our consumption.

This makes economy big and differentiated. People live in a world of strong economic rules. Not only the big players dominate and control the system as there are niches for clever programmers and those who have the best algorithms and data win the race. Only “big brains” are able to play within this system of AI and machines.

It is essential who controls the algorithms as society and the distribution of money and wealth depends on the definition of algorithms. Therefore, the system depends totally on the role of the state and its policies which define how the lives of the masses look like. Regulation makes sure that AI is controlled and RRI is part of the algorithms. All ethical and gender equality requirements are programmed into the machines, which is being enforced and controlled top-down. With this assumption of high RRI and ethical values this world consists of a wealthy society where the machines support and care for the humans and all humans get their part of the wealth. With a strict regulation and high awareness of the system and its dynamics, AI and robots provide wealthy and healthy lives for human mankind as the state provides income for everybody.

To be able to control such a system high education and awareness are needed and therefore very high values. EU funding is policy driven and functions top-down, in mission-oriented calls (TRL, segment, etc.) with medium-low risk.

AM technologies are highly automated and reliable. In the people-free factories no human input is needed for the manufacturing process as the technology is completely mature. Highly educated people are needed for the development and maintenance of the AI in the companies dealing with AI solutions. Less educated people lose their jobs. Human skills are needed only for the development and control of the AI as computers and machines are everywhere. Everything is automated and digitalized.

Business models are based on the principle of online ordering and production on demand, which is supported by AI. AM is used for all possible applications. AM high-end applications are used for

physical or mental augmentations and medical use. Also, weapons research (drones, light weight equipment) is important. Public engagement will be higher because of reliability and is also more common to talk about AM (science education).

Very strict regulations will be applied all over the world with AM processes and products highly regulated and certified. Some technologies and solutions may disappear due to strict environmental and safety and security regulations. Harmonized regulation worldwide makes global market grow.

The machines need a lot of energy. Therefore, AM is a solution. Innovation is mostly closed with stronger patent protection, proprietary standards, strong national interests, higher specialization, and efficiency.

AM added value and supply chains are relying on AI algorithms, licences etc. Artificial intelligence defines collaboration. Therefore, algorithms define the way and quality of collaboration.

Consequences for Scenario D "Robots' world"

Risks

The direction of needs might be controlled (manipulation of people). Freedom of choice might possibly be restricted. The question will be how freely we can decide what we want to have when the available resources (income) are limited.

There might be no individualisation in the scenario. AI makes decisions and might become critical for human beings because of a lack of holistic ethical considerations. Ethical questions will increase significantly because competences and decision-making power will be handed over to AI.

The high concentration of decision-making power on AI and algorithms might control and manipulate human beings and their decisions (competition of communities, hackers). The human beings are no more able to understand and reconstruct the AI decisions. Fears will also arise from the obvious realisation of the loss of control.

Robots and AI overshadow this scenario. AM gets covered.

The challenge of retaining decision-making authority versus decision-making based on AI is seen critically.

Opportunities

In 2040, there will still be some developments that bring AM in the direction of "mass individualisation" and drive its use as a production technology.

This demand requires an automated implementation of the constructive realisation of product ideas, which means that the AM software value chain is to be strengthened through AI.

People will have access to knowledge, possibly there is less interest from society because there is a high basic supply, also AI can control the selection of topics and favour certain topics (bias for certain topics). Power claims to determine the degree of openness. AI itself is a partner in the innovation process. AM is driven by AI (construct products or process chain).

Conclusion

The foresight work in IAMRRI project puts the AM webs of innovation value chain in a broader context and develops future scenarios with specific emphasis on the innovation value chain and RRI aspects there. The developed four scenarios are about “responsible Europe”, “self-organizing society”, “elites of money and knowledge”, and about “robots world”, each in the field of AM and with RRI aspects.

AM (formerly known as 3D printing) has been around for 30 years. Back then, it was a big challenge to create a 3D model with the computer. It was difficult to design the products because the computer and graphic power was not available, this was a big challenge. Nowadays there is convergence between software, between digital twins and material technologies and with printing machine technologies. These trends correspond to a great extent with the "robot world" scenario. During the IAMRRI Future Talk, AM specialists explained that a lot of research is currently being done on materials, the interplay of material microstructure, process parameters and behaviour of the manufactured parts. AM promotes learning about materials and manufacturing processes. In the future, there will be new and very interesting research on materials with new functionality, such as graded material, new compositions and locally different functional properties.

Big players are becoming more aware of market opportunities that are still seen as more niche, but they will have projections of exponential growth. In the medical field, there are already big players, but they are not fully exploiting the new market options for the specific and individual medical application of AM products. This fact gives small entrepreneurs the opportunity to enter this market, production and value chain. How long this trend will last is the crucial question, as the developed scenarios show?

The consequences for the innovation phase in each of the scenarios and especially the RRI consideration provide input for the AM model developed in this project. Regarding some important technological aspects, the development in AM and in AI promote each other. Although, this dependency is worked out in the scenarios “elites of money and knowledge” and “robots world” especially, AI plays its role also in “responsible Europe” and in “self-organizing society”, because AM is also a lot of data, software, and design driven. From an innovation systems point of view the basis for innovation is collaboration and networking. It must be ensured that all those involved also gain value. Regarding AM value chains on a high geographical level, we learn that if RRI was only implemented in Europe it could still be example for the world. However, when running a global business, and AM works globally and is very divers, even in the two cases we consider in IAMRRI, automotive and medical application, further strategies must be developed for bridging RRI and global competitiveness. This exercise of foresight in this project should open up the scope of thinking, should enlarge possible directions. Foresight is not a prediction. It opens the possibilities for actions and reactions. In this IAMRRI case the scenario development is one of the foresight methods which are linked to stakeholder involvement. This combination is already addressing the RRI process dimension. The involvement of “relevant” stakeholders is crucial in such studies. The best results and the best impact are achieved if the affected stakeholders also have the power, the urgency, and the legitimacy for the transfer of the results into strategies. This is the limit of this study. The IAMRRI foresight was organized in three workshops, however with different stakeholders in each workshop mostly. Only the core team participated in each of the workshops. This is because

of the limits of resources of IAMRRI. Unless this fact, foresight process co-created a common communicable and well-structured picture and awareness within stakeholder groups about future shapes and strategies for AM and for webs of innovation value chains in AM with openings for RRI through a diverse & inclusive, anticipative & reflective, open & transparent, and responsive & adaptive to change process. The outcome of the applied foresight process in IAMRRI are manifold. AM was put in a broader context and besides technological aspects also societal, economic, environmental, policy, and ethical factors are considered. Future strategies, future shapes, scenarios for the AM dynamic webs of innovation value chains and their openings for RRI were developed with a time horizon of approximately 20 years. In addition, the developed scenarios and their consequences delivered input to the simulation work here and will be compared with the developed model.

The recipient of the foresight outcome, the future shapes of AM WIVC will be the EU AM Community, the EU Commission, the RRI community, the stakeholder community and science community.

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Different futures for the European innovation system of additive manufacturing and their implication on society

ABSTRACT

Foresight methodologies offer an excellent approach for discussion a technology on an innovation ecosystems and society level. Foresight brings in various perspectives and puts the thematic focus into a broader context and bridges the challenges with societal needs. This article outlines four different future scenarios for AM and its relation to responsible research and innovation (RRI) and delineates consequences out of these scenarios. Additive manufacturing (AM) refers to a whole bundle of technologies. Software technologies, design technologies, digital twins, material and machine technologies combine to form a high-tech system. These very dynamic developments are an interesting object of investigation for the approach of Responsible Research and Innovation (RRI). There is a strong link to digitalization especially regarding data for construction plans. The innovation phase is characterized by strong interlinkage between data provider, software engineers, AM machine engineers, powder producers. In the IAMRRI EU project innovation value chains were investigated. The IAMRRI project dealt especially with the impact of such technologies on a broader scale. For defining the scope IAMRRI project has worked out future scenarios. The frame for such scenarios is not only the technological capabilities but also the societal, economic, and policy perspectives. The scenarios were developed in stakeholder workshops.

Key words: Foresight; scenario technique; additive manufacturing; responsible research and innovation (RRI).

Introduction

Additive manufacturing (AM) has gained importance in the last decade. AM has many advantages such as directly manufacturing finished component, reduce time to market by accelerating prototyping, shorten supply chain, on-demand manufacturing, or fabricating custom implants, such as hips and prosthetics. These advantages have helped in taking it to the next level of customized functional end use products. The possible applications are manifold including the areas of aerospace, medical, automobiles, etc. AM is closely linked to software and data because of preparing the design and structure information of the component to be printed. Thus, artificial intelligence and machine learning are becoming integral parts of AM growth. The IAMRRI project investigated, described, and modelled the webs of innovations value chains (WIVC) in the sector of AM with openings for responsible research and innovation (RRI). In addition, a foresight study was accomplished for considering the bund of AM technologies in a broader context. The AM technologies were analysed with stakeholders from outside the project and with factors from societal – cultural, technological, economic, ecological, policy, legal, and ethical aspects.

Foresight in combination with stakeholder involvement was applied as an excellent foundation for accomplishing concrete strategies and actions within the AM innovation system and especially within the WIVC in AM. There are various approaches and methodologies for developing future

studies for AM such as Delphi study, trend analysis, workshops with experts, or roadmaps. The applied scenario technique approach in IAMRRI needs well-defined groups of participants. At the best, relevant participating stakeholders have the power, the urgency, and the legitimacy (see Mitchell et al. 1997) to have an impact within the system. In this case of the AM WIVC triple helix actors (actors coming from science & research, from industry & business, and from public authorities) are involved. The applied foresight approach was the scenario technique with triple helix stakeholder involvement. The RRI process dimensions are covered easily by this approach as the foresight process design was given by co-creation of future scenarios with stakeholder involvement, which is diverse & inclusive, anticipative & reflective, open & transparent, and responsive & adaptive to change. The RRI policy agendas or RRI keys, such as ethics, gender equality, public engagement, science education, open access, are analysed and worked out for each scenario and accompanied the foresight process from the beginning.

The scenario process starts with a context analysis. Trends, drivers, all aspects, which affect, boost, enhance and hinder directly or also indirectly the WIVC of AM are analysed and assessed. The outcome of the context analysis is a list of key factors, a foundation for developing future alternatives. The various future shapes let derive consistent scenarios and investigate consequences and wild cards from the developed scenarios. The time horizon for the foresight outcome will be approximately 20 years.

The structure of this article is divided into Introduction, which provides the context and objectives, methodology, results, and conclusion.

Context to Literature

The frame of the IAMRRI scenario development covers a meta level, a systems point of view. There are several future studies in scientific literature. Gebler et al. 2014 investigate the cost-effectiveness and sustainability of AM. AM has a manifold application potential. For instance, there are studies for the application of AM in cultural heritage (Balleti et al. 2017). Considering the various futures of all these different possibilities goes far beyond this report. We focus on AM in general and especially with application potential in automotive and medicine. Bhattachrjya et al. 2014 investigates prospects of AM and discusses perspectives in healthcare, automotive, aerospace, consumer durables, and special consumer products, tools for assembly. Johnston et al. 2018 emphasis on security issues. In long-term, AM will change the value chains, which already starts with the innovation phase (Bromberger & Kelly, 2017). Digital technologies highly impact AM. These two technology approaches interact and promote each other. Riemer et al. 2019 developed three scenarios for Germany in 2025. They talk about “revolution from the niche”, “interlinked digital manufacturing succeeds” and “system providers under increasing pressure”. Gausemeier et al. 2011 describe futures in AM based on scenarios which match technology push and market pull and analyse this with a DELPHI study. Ryan et al. 2017 study the literature about scenarios for supply chains. Caviezel et al. 2017 deals with technological, economic, and ecological issues of AM and illuminates the technologies and experiences regarding possible health effects as well as risks for internal and external security. Trevor et al. 2018 study security implications in AM and summarize them in scenarios. Jiang et al., 2017 for instance, have studied the AM literature and have

characterized and prepared the results for conducting a DELPHI study and a DELPHI projection. The IAMRRI scenarios are linked to the studies of Gausemeier et al. 2011, Ryan et al. 2017, Caviezel et al. 2017, Trevor et al. 2018 respectively. Jiang et al 2017 is connected to each of the IAMRRI scenarios from an AM technical aspect.

Methodology

There are different scenario techniques e.g., experts write various narrative future scenarios (Gaßner R.; Steinmüller K., 2018). The scenario development applied here follows the process introduced by Ute von Reibnitz (1992) and others. This highly structured process is combined with a stakeholder co-creation work. The applied procedure for the whole scenario development in IAMRRI can be summarized in the following six steps.

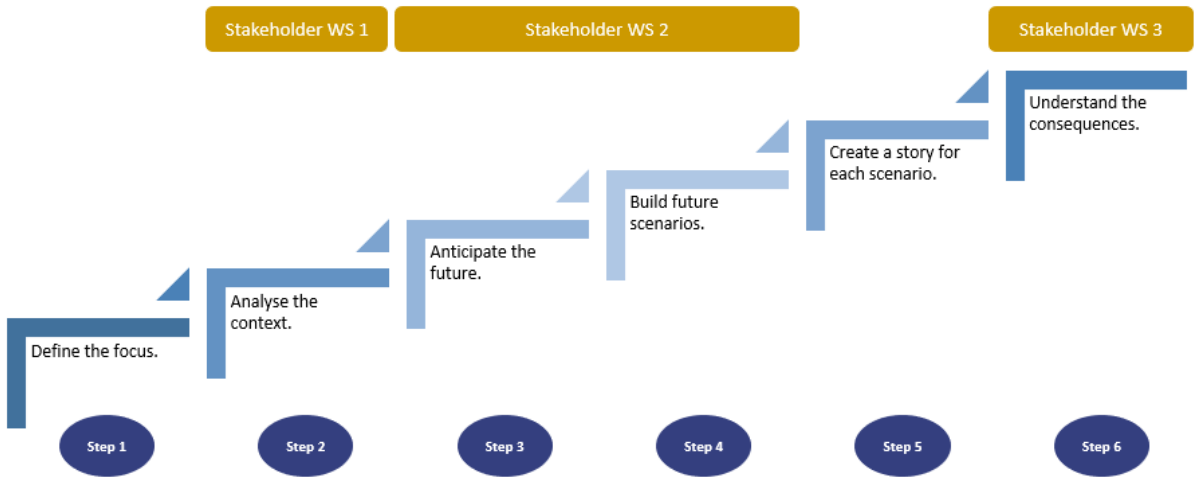

Figure 1: The steps in the applied scenario technique in the IAMRRI foresight.

The starting point, the focus here is the AM innovation value chain and possible openings for responsible research and innovation. AM is a broad field. In this case AM is considered in general with focus on automotive and medical applications. The context analysis is conducted by an analysis of influencing factors structured according to societal, technological, economic, environmental, policy, legal, and ethical aspects (STEEPLE). This assessment of these influencing factors leads to the key factors. Several methods for the assessment of the influencing factors were applied, namely an uncertainty / impact analysis, a cross-impact analysis, and a social network analysis. These methodologies are explained and described in a lot of respective literature.

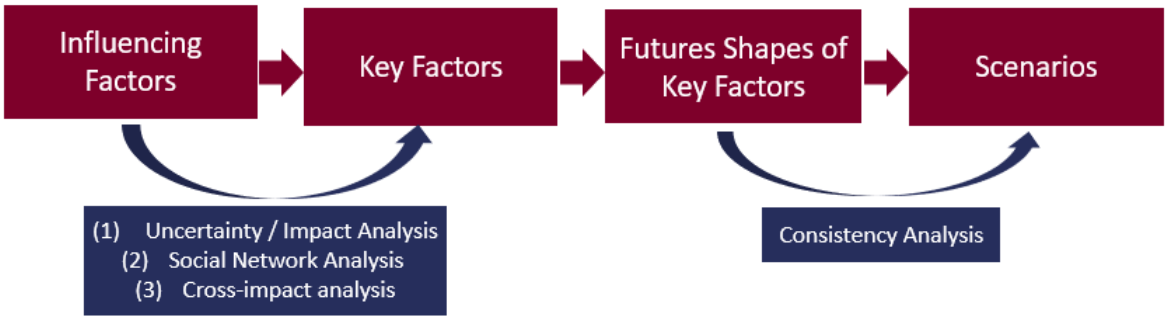

Figure 2: From influencing factors to future scenarios.

For each key factor, however, extreme projections are formulated, which should be as distinct as possible. The timeframe is approximately 20 years ahead. For building future scenarios several methodologies can be implemented to get meaningful and consistent future scenarios. Generally, there is the intuitive holistic way, or there are systematic analytical methodologies. When working with stakeholders we reach for an intuitive holistic approach. A morphological analysis is conducted with all key factors and their future shapes. The bundles of futures shapes, one from each foresight key factor, tells us already the core content of a scenario. The analysis of the consequences in each scenario is the next step. The opportunities and risks in each scenario are discussed. In this case, also the RRI aspects in the innovation process are specifically worked out for each scenario. The three stakeholder workshops took place in the frame of the IAMRRI project. The first workshops were performed in Metz in France with the network of MATERALIA (March 2019), the second in Bilbao with the stakeholder network of TECNALIA (October 2019). And the third workshops took place with the stakeholder network of the Additive Manufacturing Austria platform, online because of COVID restrictions (February 2021).

Results

Each step of the procedure of this approach provides a result, which is the input for the next step. The context analysis presented a list of 56 influencing factors. This list of these 56 influencing factors is described in deliverable D6.2 “Summary of key factors” of the IAMRRI project. The importance-uncertainty rating resulted in 45 factors. The applied cross-impact analysis and a social network analysis together with a stakeholder workshop eventuated in 14 key factors. For each of the 14 key factors different disjoint future shapes were developed. These futures of the key factors provide the foundation of the scenarios, which are built on the consistency of the different future shapes. The details of this outcome are documented in deliverable D6.3 “Report on AM Future Scenarios and Strategies”. In this article puts the work in a scientific context.

Future shapes of the 14 key factors

For each of the foresight key factors two to four different future shapes are developed. The better the different futures of one foresight key factor are described, the better disjoint these future shapes of one and the same foresight key factor, the clearer the different scenarios will be. Some of the boxes are empty. This is because for this key factor no more disjoint future shapes were found.

Table 1: The key factors and their various future shapes.

	Key factor	Future Shape A	Future Shape B	Future Shape C	Future Shape D
1	**Business models**	Products on demand	Responsibility for application		
2	**Effects on other global supply chain**	One step supply chain	Tax disruption	Negative CO_2-footprint	Multicorporate enterprise acting on global level
3	**Regulation**	Very strict regulation all over the world	Lose regulation all over the world	Different regulations regarding strictness and geography	
4	**Education and skills development**	No education and skills needed	Education focused on technical skills	Education focused on creativity	
5	**Trust, reliability, responsibility, sustainability**	"Capitunism" (this means capitalism & communism)	The lucky one always wins (polarisation)	Democratic open societal makers	"Who cares!"
6	**Lobbying activities and strategic market development**	Finished successful lobbying	On-going sustaining lobbying	Contra\backslash (too strong lobby, opposite effect, no support)	Closed down, AM prohibited
7	**Collaboration of different stakeholders**	Customer-centric collaboration (e.g., surgeon)	Artificial Intelligence defines collaboration		
8	**Cultural norms & values (including gender equality)**	Gender equality as a matter of fact	Sustainability and responsibility values	Neo-realism & plutocracy & nationalism (War/unrest)	
9	**Building of critical masses**	Education (existing critical masses)	Niches (no critical masses)		
10	**(Public) Awareness of advantages**	Science faction	Men's domains	Poisoning: Everybody is aware of toxicity and risks of materials for AM	Robot knows
11	**Sufficient maturity of printing technologies**	People-free factory	De-centralized production		
12	**Less usage of resources**	Expensive resources	Cheap resources		
13	**Funding possibilities**	EU top-down funding	EU bottom-up funding		
14	**Open innovation and free transparency of production process**	Mostly open	Mostly closed		

Consistent bundles of futures shapes

There are several methodologies to create meaningful and consistent future scenarios. When working with stakeholders the holistic way seems to be appropriate. For conducting this a morphological analysis supports the work. Each key factor is put on the top. Below the different future shapes of each key factor are posted. The next step is to match the future shapes, which means, take one future shape of each key factor, and combine it to a future shape of the other key

factor. These two future shapes should be consistent. Identifying a bundle of consistent future shapes, where each key factor represented is the basis for the scenarios. The lines (based on the coloured dots) form such bundles. Each of such a bundle leads to a future scenario.

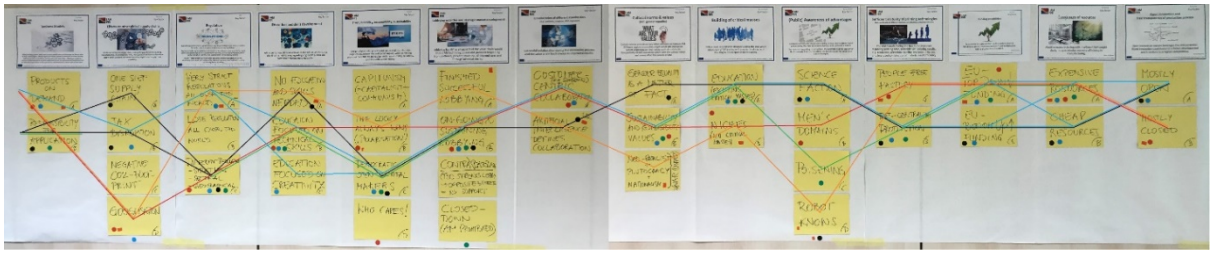

Figure 3. The morphological analysis[1].

IAMRRI future scenarios

Based on the intuitive approach with the morphological analysis the following four future scenarios were identified and described. In the scenario development workshops we work with colours so that we can easier distinguish between the contributions and assign the results to the specific scenario. Therefore, also here the scenarios are marked in corresponding colours.

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

(A) Responsible Europe - sustaining AM system in a well-structured Europe

Sustaining AM system in a well-structured Europe. "Service Provider", consumer purchasing remains in conventional sales channels.

[1] The term morphology comes from antique Greek (morphe) and means shape or form. The general definition of morphology is "the study of form or pattern. (Fritz Zwicky, 1966).

General Morphological Box (analysis) is a method for investigating the totality of relationships contained in multi-dimensional, non-quantifiable problem complexes.

In this scenario the "European" way is continued. In a well-structured world of openness and regulation ethical values, democracy, sustainability, and education are high values within policy and society. Society is built by democratic open societal makers. There are many options to choose for the individuals. Science education becomes more important. Also, public engagement and ethics become more important to individuals.

Education is focused on technical skills, on knowledge and on creativity. It has undergone radical change as it also focuses on creative thinking. AM is also integrated into curricula, and there is an open access system. Society works closely together with engineers. Toolboxes are available for non-technical trained people to solve technical problems. Training of engineers is more holistic and integrates non-technical topics, such as RRI orientation.

Regulations are harmonized and strong. Regulation covers standardisation and legal requirements. They give a secure framework for broad applications of the technology. Some technologies and solutions may disappear due to strict environmental and safety and security regulations. Harmonized regulation worldwide makes global market grow. Ethical values are defined by the society. Ethical panels decide on the framework of these ethical values.

The highly esteemed RRI keys are implemented. Science education, public engagement, and ethics become more important to individuals. There is more open access and more gender equality. Sustainability and responsibility are high values, i.e., waste reduction, and less use of resources as well as circular economy.

There is high awareness in society, so everybody is aware of the risks of AM raw materials and the AM technologies, products. Also, resources are a high valuable good. AM could be a solution with e.g., innovative lightweight solutions and product designs. There is tax on pollution (material, equipment), e.g., taxes for those who will produce waste, and taxes on data.

In this conservative scenario there is only incremental improvement of the AM production system which is mostly open, and user/customer centred. AM is a standard technology used wherever needed. Harmonized and strong regulations give a secure framework for broad applications of the technology.

AM webs of innovation value chain have undergone a consolidation process. AM added webs of value chains and supply chains might be dominated by large global active companies. The monopoly on machine selling, licensed models, licensed designers etc. but the production and innovation process on new products is open for other players, with low barrier access to patents and user-centricity. RRI is reflected in the new products and manufacturing process because ethical aspects, gender, society needs are taken into account. There is still a great variety of possibilities for smaller companies and there is strong knowledge flow but limited by regulation.

AM business models are based on the principle of online ordering and production on demand, which requires know-how on the customer side. Factories are micro-factories, localized where they are needed (neighbourhood, city, etc.). AM production system is decentralized and can be globally.

Consequences for Scenario A "Responsible Europe"

Risks In this scenario regulations are very strong. It could happen that this system is overregulated. Taxes and data tax might not lead to a boost either, every

megabyte might be taxed. This could lead to compulsion on efficiency, but also might inhibit development. AM might therefore remain a niche topic in Europe as it is in the current situation. The innovation power in Europe might be lost especially because of the very strong regulations. Material development, or plant and machine development might be difficult because of the strong regulations and taxes. In case the world outside Europe does not care about responsibility, it would be a big challenge for providing "responsible technology" from Europe to the whole world.

Opportunities Smaller companies (idea generation) might have more opportunities for innovation but might be bought by a big company afterwards. This is due to more flexibility for SMEs.

Innovation might still be implemented by large companies (idea development and idea dissemination). The likelihood for success on the market is higher than for small companies because of their market power.

Standardised materials and equipment might affect higher quality in AM (e.g., Stratasys works).

Regulation such as standardisation might have a positive impact on stable technologies and AM processes, because research organisation, industry, and politics have agreed on a common understanding.

(B) Self-organizing society - AM maker communities and individuals

AM maker communities and individuals "Content Provider", consumer purchasing shifts to online file-sharing repositories.

Differentiation, democracy, individual solutions, and knowledge society are the keywords in this scenario. In this colourful and diverse world individuality is the highest value of all. Individuals share a common understanding of high ethical values. Everybody is responsible for themselves, their education, and their jobs. They have so many possibilities that it is hard to find a "red line". Regulation varies and is not well established everywhere. The innovation and education systems are open and transparent but not harmonized. Education is a good for everybody and a very high value.

Democracy, ethical values, and personal rights are very high values of society. Everyone aims at freedom for themselves and society. Therefore, there are fair social conditions built in a bottom-up way. Sustainability and social welfare and balance are principles on which society and individual decisions are based.

There are no common standards or rules. Regulations are very different regarding their strictness, the sector addressed and the geographical area. Concerning AM there would be a need of regulation and control of what is printed. Also, the taxes which apply tax on material/data and equipment are not harmonized.

The implementation grade of RRI is different based on the geographical area and sector but with a generally high open access to knowledge, innovation, and science education. Gender equality is a matter of fact, there is no loss of talent. Information and knowledge are shared and tools for

collaborative work are common. Sustainability and responsibility are high values, i.e., waste reduction, and less use of resources as well as circular economy. Everybody is aware of the toxicity and risks of AM raw materials.

Government has increased possibilities, but the policy system is more complex. EU funding works bottom-up as there are open calls for all entities with high-risk projects, market and entity driven. Interdisciplinarity is important.

There are many highly innovative specialists and experts. Critical masses on AM are already existing and AM is integrated into curricula. AM education is focused on technical skills.

The AM production system is decentralized as AM products are printed at home or in maker spaces. Everybody has the capability to print at home and his/her own short supply chain. Not the products are sold but the value (e.g., orthoplastic versus warranty). There is a great variety of products. Everybody needs to take responsibility for the whole product life cycle (engineering, dismantling).

The production process is mostly open, with cheaply usable patents, open access to publications. There is great knowledge flow. Open innovation gives a high diversity and easy access to take part in innovation.

Consequences for Scenario B "Self-organizing society"

Risks	High quality might not be guaranteed.
	AM production might require a lot of skills/knowledge for producing a desired and certified product.
	IPRs management might be crucial in this scenario.
Opportunities	Since AM production requires expertise, it might be an opportunity for setting up a good production and business for high-tech AM products.
	Open innovation and open access in this scenario might be great opportunities.
	High acceptance of the technology by the society.
	Since encapsulated safe printing machines are available, the work in maker spaces and at home might offer a lot of possibilities.

(C) Elites of money and knowledge - powerful and mature AM industry

Powerful and mature AM industry "Market Explorer". Use of AM to enhance existing business models.

In this world of geographical and societal imbalances society is dominated by elites who own money and knowledge. Economy is dominated by only a few powerful enterprises. AM is a mature, highly automated, reliable, and efficient technology. RRI principles are tried to be implemented top-down, but they are not of societal interest. There is no gender equality. Only concerning resources, efficiency is a high value due to resource scarcity.

In this scenario society is split and there is a large gap between rich and poor. Most people live in crowded mega-cities in small flats or even around them in slums. They work on the few occasional

jobs that are available. Most of the work is done by machines. Those who live in the countryside earn their modest living working for large farms together with machines.

Most of the people do not have access to higher education so they have no chances to get well paid jobs (poor science education). Only the rich and well-educated elites have the possibilities to provide higher education to their children. Their job is the development and control of machines. They have a very good life which is well-assisted by robots. Those who have the luck to get a good job in a position where humans are still needed, e.g., in creative positions work day and night, to be able to survive and earn the money they need and keep their jobs.

RRI principles are not implemented. There is no gender equality. Science education is underrepresented. Only concerning resources, efficiency is a high value due to resource scarcity.

Regulations are very different regarding their strictness, the sector addressed and the geographical area. Regulation is not harmonized at all. Big markets protect each other (US, Europe, Asia). The global market could fall apart into different protected markets.

EU funding functions top-down, in mission-oriented calls (TRL, segment, etc.) with medium-low risk. Big enterprises have the power to get funding, small players have no chance to be part of the WIVC. Public is not engaged in the innovation process at all.

AM Economy, AM value chains, and supply chains are dominated by only a few powerful organisations having the monopoly on machine selling, licensed models, licensed designers etc. AM is a mature, highly automated, and reliable technology. In the people-free factories no human input is needed for the manufacturing process because the technology is completely mature. Additive manufacturing is a standard technology for the wealthy society. It cannot be used by the masses as they do not have the financial, technological and know-how recourses. AM plants are in all places of the globe for producing the products needed there. These plants belong, of course, to the elites.

Innovation is mostly closed with stronger patent protection, proprietary standards, strong national interests, higher specialization, and efficiency.

AM education is focused on technical skills. The education system is like the status quo (today). It focuses primarily on technical skills rather than on knowledge and science education. STEM degrees are the most popular. Companies are full of highly specialized technicians. It is hard to find these profiles due to high demands, but the job options are limited.

Resources are exploited and therefore already rather expensive. AM could be a solution with e.g., innovative lightweight materials. The use of AM could help to preserve resources and support sustainability and responsibility which are not high values everywhere. AM players are aware of the risks of the material and technologies e.g., toxicity of some AM materials.

Consequences for Scenario C "Elites of money and knowledge"

Risks

Basically, this is an anti-innovation scenario. The elites earn and optimise their money. Innovations might happen only when pressure comes to the system like scarce resources forcing the elites to innovate to keep their financial advantage. For the "normal population" there is hardly any access to resources.

Here there is the risks of monopoly from a few actors (software, material, and

machine providers). The monopoly situation induces also risks regarding agreement between material and machine providers, licence, etc.

AM has a risk to follow "older" industry regarding the gender equality imbalance if no specific action is done. AM can remain a tech for advanced countries and companies. AM components can remain for advanced and developed products for "elite" people. Some might think that "from low-tech to high-tech" and especially from the simple idea "in a garage" to production for the "globe" is only possible with a lot of money. However, in this scenario, the path of success created with little money will not be possible, because the elites will not allow it or buy it up.

Opportunities There will be shadow economy with AM within the poor population. However, this is also an opportunity for ingenious ideas in the low- and high-tech sector (ideas of business and technologies "out of the garage"). Really important is only that the product, the machine, and the process are ready for the market. However, some centralized major actors could simplify the value chain and rule the normative aspect of the market. A decentralization of the manufacturing system is likely to happen with the democratisation of this mean of production (1000 people build 1 product instead of 1 factory building 1000 products).

AM can develop low-budget production, high quality production with a low-budget equipment. It can also have an influence on the education system. Since RRI is implemented more and more woman will work in R&D departments.

This scenario has also implemented artificial intelligent technologies and therefore, AM would have a good chance because AM is very digitalised and thus plays into the hands of robotics developments and AI. AI algorithms might develop AM further.

(D) Robots' world - Artificial Intelligence

Artificial Intelligence serves the world "Mass Customizer". Use of AM to create new business models.

In this scenario the world consists of smart systems everywhere. Artificial intelligence (AI) and robots replace human beings in the production process. The machines serve all humans for wealth and prosperity. Humans have more spare time as the machines do all the hard work. Data on humans is collected and used by AI, and consumption is steered.

RRI is part of the algorithm. Which RRI aspects are programmed into the AI and robots is defined by the people with force. However, the general education level is high. The machines and robots work for the human's wealth and prosperity. There are scepsis about implementing differentiated ethical values. It might not be possible to develop algorithm for a differentiated and broad ethical framework.

The system depends totally on the role of the state and its policies which define how the daily lives of the masses look like. With a strict regulation and high awareness of the system and its dynamics, AI and robots provide standardised wealthy and healthy lives for human mankind. The basis of

wellbeing and peace for humans in this system is secured to a reasonable extent. (Higher/academic) education system and an unconditional basic income are available to everyone. AM products are mass customized.

The houses are smart homes where e.g., the refrigerator is able to refill itself, and a lot of daily life products are identified as being able to be delivered by AM technology immediately and regionally either to your own houses or ordered and produced on demand at AM manufacturing sites. All paths and actions of humans are traced digitally, so huge amounts of data are produced which represent the daily needs, the decisions taken, and the values shared. As data is collected Artificial Intelligence algorithms use it to rule/control our world in a hidden way, thus consumption is steered by AI systems. All areas of life are controlled by AI, medical services, car driving, shopping, et. It is essential who controls the algorithms as society and the distribution of money and wealth depends on the definition of algorithms.

An unconditional basic income for everyone is a profound basis for wealth and peace in this system and is possible because of the efficient and responsible application of technologies for the wealth of humans. Therefore, humans have more spare time and most of us a good life as the machines do all the hard work. However, human decisions are controlled by the AI system providing an environment that uses the data on us and steers our consumption.

This makes economy big and differentiated. People live in a world of strong economic rules. Not only the big players dominate and control the system as there are niches for clever programmers and those who have the best algorithms and data win the race. Only “big brains” are able to play within this system of AI and machines.

It is essential who controls the algorithms as society and the distribution of money and wealth depends on the definition of algorithms. Therefore, the system depends totally on the role of the state and its policies which define how the lives of the masses look like. Regulation makes sure that AI is controlled and RRI is part of the algorithms. All ethical and gender equality requirements are programmed into the machines, which is being enforced and controlled top-down. With this assumption of high RRI and ethical values this world consists of a wealthy society where the machines support and care for the humans and all humans get their part of the wealth. With a strict regulation and high awareness of the system and its dynamics, AI and robots provide wealthy and healthy lives for human mankind as the state provides income for everybody.

To be able to control such a system high education and awareness are needed and therefore very high values. EU funding is policy driven and functions top-down, in mission-oriented calls (TRL, segment, etc.) with medium-low risk.

AM technologies are highly automated and reliable. In the people-free factories no human input is needed for the manufacturing process as the technology is completely mature. Highly educated people are needed for the development and maintenance of the AI in the companies dealing with AI solutions. Less educated people lose their jobs. Human skills are needed only for the development and control of the AI as computers and machines are everywhere. Everything is automated and digitalized.

Business models are based on the principle of online ordering and production on demand, which is supported by AI. AM is used for all possible applications. AM high-end applications are used for

physical or mental augmentations and medical use. Also, weapons research (drones, light weight equipment) is important. Public engagement will be higher because of reliability and is also more common to talk about AM (science education).

Very strict regulations will be applied all over the world with AM processes and products highly regulated and certified. Some technologies and solutions may disappear due to strict environmental and safety and security regulations. Harmonized regulation worldwide makes global market grow.

The machines need a lot of energy. Therefore, AM is a solution. Innovation is mostly closed with stronger patent protection, proprietary standards, strong national interests, higher specialization, and efficiency.

AM added value and supply chains are relying on AI algorithms, licences etc. Artificial intelligence defines collaboration. Therefore, algorithms define the way and quality of collaboration.

Consequences for Scenario D "Robots' world"

Risks

The direction of needs might be controlled (manipulation of people). Freedom of choice might possibly be restricted. The question will be how freely we can decide what we want to have when the available resources (income) are limited.

There might be no individualisation in the scenario. AI makes decisions and might become critical for human beings because of a lack of holistic ethical considerations. Ethical questions will increase significantly because competences and decision-making power will be handed over to AI.

The high concentration of decision-making power on AI and algorithms might control and manipulate human beings and their decisions (competition of communities, hackers). The human beings are no more able to understand and reconstruct the AI decisions. Fears will also arise from the obvious realisation of the loss of control.

Robots and AI overshadow this scenario. AM gets covered.

The challenge of retaining decision-making authority versus decision-making based on AI is seen critically.

Opportunities

In 2040, there will still be some developments that bring AM in the direction of "mass individualisation" and drive its use as a production technology.

This demand requires an automated implementation of the constructive realisation of product ideas, which means that the AM software value chain is to be strengthened through AI.

People will have access to knowledge, possibly there is less interest from society because there is a high basic supply, also AI can control the selection of topics and favour certain topics (bias for certain topics). Power claims to determine the degree of openness. AI itself is a partner in the innovation process. AM is driven by AI (construct products or process chain).

Conclusion

The foresight work in IAMRRI project puts the AM webs of innovation value chain in a broader context and develops future scenarios with specific emphasis on the innovation value chain and RRI aspects there. The developed four scenarios are about “responsible Europe”, “self-organizing society”, “elites of money and knowledge”, and about “robots world”, each in the field of AM and with RRI aspects.

AM (formerly known as 3D printing) has been around for 30 years. Back then, it was a big challenge to create a 3D model with the computer. It was difficult to design the products because the computer and graphic power was not available, this was a big challenge. Nowadays there is convergence between software, between digital twins and material technologies and with printing machine technologies. These trends correspond to a great extent with the "robot world" scenario. During the IAMRRI Future Talk, AM specialists explained that a lot of research is currently being done on materials, the interplay of material microstructure, process parameters and behaviour of the manufactured parts. AM promotes learning about materials and manufacturing processes. In the future, there will be new and very interesting research on materials with new functionality, such as graded material, new compositions and locally different functional properties.

Big players are becoming more aware of market opportunities that are still seen as more niche, but they will have projections of exponential growth. In the medical field, there are already big players, but they are not fully exploiting the new market options for the specific and individual medical application of AM products. This fact gives small entrepreneurs the opportunity to enter this market, production and value chain. How long this trend will last is the crucial question, as the developed scenarios show?

The consequences for the innovation phase in each of the scenarios and especially the RRI consideration provide input for the AM model developed in this project. Regarding some important technological aspects, the development in AM and in AI promote each other. Although, this dependency is worked out in the scenarios “elites of money and knowledge” and “robots world” especially, AI plays its role also in “responsible Europe” and in “self-organizing society”, because AM is also a lot of data, software, and design driven. From an innovation systems point of view the basis for innovation is collaboration and networking. It must be ensured that all those involved also gain value. Regarding AM value chains on a high geographical level, we learn that if RRI was only implemented in Europe it could still be example for the world. However, when running a global business, and AM works globally and is very divers, even in the two cases we consider in IAMRRI, automotive and medical application, further strategies must be developed for bridging RRI and global competitiveness. This exercise of foresight in this project should open up the scope of thinking, should enlarge possible directions. Foresight is not a prediction. It opens the possibilities for actions and reactions. In this IAMRRI case the scenario development is one of the foresight methods which are linked to stakeholder involvement. This combination is already addressing the RRI process dimension. The involvement of “relevant” stakeholders is crucial in such studies. The best results and the best impact are achieved if the affected stakeholders also have the power, the urgency, and the legitimacy for the transfer of the results into strategies. This is the limit of this study. The IAMRRI foresight was organized in three workshops, however with different stakeholders in each workshop mostly. Only the core team participated in each of the workshops. This is because

of the limits of resources of IAMRRI. Unless this fact, foresight process co-created a common communicable and well-structured picture and awareness within stakeholder groups about future shapes and strategies for AM and for webs of innovation value chains in AM with openings for RRI through a diverse & inclusive, anticipative & reflective, open & transparent, and responsive & adaptive to change process. The outcome of the applied foresight process in IAMRRI are manifold. AM was put in a broader context and besides technological aspects also societal, economic, environmental, policy, and ethical factors are considered. Future strategies, future shapes, scenarios for the AM dynamic webs of innovation value chains and their openings for RRI were developed with a time horizon of approximately 20 years. In addition, the developed scenarios and their consequences delivered input to the simulation work here and will be compared with the developed model.

The recipient of the foresight outcome, the future shapes of AM WIVC will be the EU AM Community, the EU Commission, the RRI community, the stakeholder community and science community.

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