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Agent-based Modelling for Responsible Research and Innovation in Additive Manufacturing Innovation Value Chains: From SKIN to IAMRRI Model

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Abstract. This paper describes an agent-based model, the IAMRRI model, which includes market, innovation network, knowledge transfer, innovation value chain, dual industries, and responsible research and innovation features. Empirical data collected from the additive manufacturing industry as well as an extensive review of existing literature were used for designing the model. The IAMRRI model can be used for studying the interplays between the areas described above. A cursory implementation of the model is under development and will be released as an open-source software project. Limitations and suggestions for further research are described.

1 Introduction

The knowledge creation presented in this paper was made possible by the IAMRRI-project[1]. The project investigates webs of innovation value chains (WIVCs) in additive manufacturing (AM) and identifies openings for responsible research and innovation (RRI). Its aim is to develop a complex network model of AM innovation chains and the associated processes that are potentially relevant for RRI. There are two different industries in which AM is being used in the model—the automotive and medical industry. Knowledge transfer dynamics between broker agents in these two industries are designed.

The development of the model itself took place over three stages, all of which required extensive data collection from fieldwork, case studies and statistical data from multiple levels of observation and analysis. The first phase was 1) an extensive literature review and associated synthesis which 2) provided information that was used as a foundation for designing a conceptual network model of AM innovation chains and the associated processes. During the final stage 3) the model was implemented and adapted so that it could be used to answer the specific questions which the IAMRRI-project aimed to answer.

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This paper covers the second stage in-depth and addresses the following research question: *"How can webs of innovation value chains and RRI be most accurately described through an agent-based model?"* That is, this paper addresses the IAMRRI conceptual model. The IAMRRI model uses the SKIN[2] model as a foundation. Space limitations prohibits us from describing the selection criteria that finally led us to choosing the SKIN model as a foundation, but it involved a careful literature review starting with screening of 1864 published (and sometimes unpublished) works in academic journals, books, theses, and so on. For readers not familiar with the SKIN model, a brief description is provided. It is followed by a description of adaptations and extensions which comprise the IAMRRI model. Differences between base SKIN and the IAMRRI model are described. The product is a complex network model of AM innovation chains and their associated processes, including RRI mechanisms.

This paper and the model provided contributes to the innovation network literature by providing a mechanism of network formation and learning through its IVC extensions, the introduction of a double-industry feature that allows modellers to examine knowledge transfer dynamics between industries, and, finally, RRI mechanisms that allow modellers to simulate the effects of RRI on innovation networks, innovation value chain formation, learning, and performance.

2 Theoretical Background

2.1 Innovation Value Chains and Webs of Innovation Value Chains

Innovation value chains (IVCs) have been studied on both the abstract theoretical level and in specific industries. An Innovation Value Chain (IVC) can be understood as "a sequential, three-phase process that involves idea generation, idea development, and the diffusion of developed concepts (Hansen and Birkinshaw, 2007, p. 3). Martinsuo et al. (2019) suggest that such IVCs may co-exist and that members can take part in multiple IVCs, either at the same time or sequentially. This creates interrelated networks where innovation in one area can affect multiple innovations in other areas through knowledge transfer between participants. These supra-IVCs are termed Webs of Innovation Value Chains, or WIVCs for short.

Current studies of IVCs have substantial weaknesses. For example, Schlaile et al. (2018) showed in his review that studies of such innovation processes show little regard to bounded rationality and conflicting interests. Other weaknesses include missing such processes' dynamic nature (Chen et al., 2018), complexity (Roper et al., 2008), and multi-stakeholder nature (Olson, 2014). These weaknesses can partly be

[2] SKIN is an agent-based model of innovation networks in knowledge-intensive industries (Ahrweiler, 2017; e.g., Ahrweiler et al., 2015; Gilbert et al., 2018).

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explained by several methodological challenges. Use of panel data (Chen et al., 2018) and cross-sectional analysis (Ganotakis and Love, 2012) are useful, but also limited to shorter time horizons and unable to capture IVC dynamics. These limitations in state-of-the-art research become even more apparent when studying WIVCs.

Agent-based models are particularly useful for dealing with such issues, which is one of the reasons we decided on designing an agent-based model instead of other model types.

2.2 Responsible Research and Innovation (RRI)

The European Commission states that “Responsible Research and Innovation (RRI) 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” (European Commission, 2014). RRI was initially an amalgamation of different fields such as political science, innovation studies, gender studies, ethics, and many others, but has since come into its own as a field of research.

Readers unfamiliar with RRI research but familiar with European policy might suspect that RRI is a policy-only concept, but in fact the concept of RRI been evolving concurrently in two parallel tracks—one academic and one political (Burget et al., 2017). Whereas the political track has been pragmatic and focused on political agendas (such as gender equality and science education), the academic track has focused on abstract and conceptual issues with RRI. These tracks have inspired and informed each other in the sense that the political agendas arise from issues deemed important by the public (e.g., gender equality) and these agendas provide empirical contexts and phenomena for researchers to study (e.g., what affects gender equality dynamics).

RRI is often divided into five thematic foci (European Commission, 2014): public engagement, open access, gender, science education, and ethics. These thematic foci are considered to represent particularly salient areas where improvements can provide the greatest societal benefits. In short, public engagement can be considered to be the degree to which societal actors work together; open access refers to the degree to which knowledge is shared openly - often in an open access fashion; science education refers to the extent citizens are able to understand scientific and technological developments and therefore participate in democratic processes related to them; gender typically refers to gender equality; and finally, ethics, or “systematizing, defending, and recommending concepts of right and wrong behavior” (Fieser, 2021) has several cross-cutting concerns across all the other foci.

Are JENSEN, Evgueni VINOGRADOV, Nhien NGUYEN
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In the IAMRRI model, these foci act as phenomena that are included in the model (e.g., firms publish open access, actors make ethical judgements, representatives from the public engage in innovation processes, and so on).

3 Method – Agent-based Modelling

Much of the IVC literature is rooted in Neoclassical economics depicting managers as rational individuals (Hansen & Birkinshaw, 2007) while the recent studies point at bounded rationality and conflicting interests of the agents involved in innovation processes (see Schlaile, Mueller, Schramm, & Pyka, 2018 for a review). Presenting innovation as a linear process may be oversimplification of the constantly evolving system of emerging interactions of micro entities involved in the innovation process. Moreover, the existing literature could significantly benefit form more dynamic (Chen, Liu, & Zhu, 2018) and complex (Roper, Du, & Love, 2008) studies encompassing a multi-stakeholder perspective (Olson, 2014). These deficit of complexity in our understanding of IVC can be, at least partly, explained by the methodological challenges. Use of panel data (Chen et al., 2018) and cross-sectional analysis (Ganotakis & Love, 2012) set limits to exploring longer time-horizons required to capture the whole process of IVC development.

Even the most advanced equation-based models of IVC (Roper et al., 2008) lack temporal sophistication needed to allow for lagged innovation effects or simultaneity. These limitations of the modern state-of-the-art research become even more obvious if we move from studying single IVCs towards research on the multiple interrelated IVCs. Indeed, innovation activities cross industry boundaries (see Bornkessel, Bröring, & Omta, 2014 for a review). Cross-industry relationships along innovation value chains are argued to take a form of technological, regulatory, knowledge, market, and competence convergence (Bornkessel et al., 2014). The resulting dynamic and adaptive webs of IVCs (WIVCs) are complex to the degree that makes many traditional research methods, as, for example, causal modelling (Williams, Edwards, & Vadenberg, 2003) or equation-based modelling (Van Dyke Parunak, Savit, & Riolo, 1998), inappropriate.

This study suggests looking at WIVCs from a complexity theory perspective. Agent-based simulation is argued to be an adequate methodological approach to considering such a complex adaptive system.

ABM is “a form of computational modelling whereby a phenomenon is modelled in terms of agents and their interactions”, where an agent is defined as “an autonomous computational individual or object with particular properties and actions” (Wilensky and Rand, 2015, p. 1). There are three primary reasons we chose an ABM approach (Wilensky and Rand, 2015):

Are JENSEN, Evgueni VINOGRADOV, Nhien NGUYEN
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First, by agent-based modelling one can model a heterogeneous population of actors who interact with each other and with the environment in a complex system with unpredictable results. Additive manufacturing is an emerging technology used in a fast-changing environment involving interactions among a multitude of actors. An innovation system (specifically in the AM industry) is a complex system. Thus, the advantages offered by ABM make this method well suited to modelling the additive manufacturing ecosystem consisting of multiple agents interacting with each other and their environment.

Second, ABM does not require any knowledge or assumptions about higher level phenomena resulting from the agents' activities; only individual-level behaviour is specified in the model. Since additive manufacturing is an emerging technology, little is known about the operating mechanisms of the additive manufacturing industry at the aggregate (industry or market) level. It is easier to describe the characteristics of individual actors than to create a causal description of the whole system. This makes ABM a natural choice of method for studying this field.

ABM enables us to "move beyond a static snapshot of the system and toward a dynamic understanding of the system's behaviour", providing us with a "rich and detailed account of the process of a system's unfolding in time, and not just the final state of the system" (Wilensky and Rand, 2015, p. 36). One key requirement of our model is that it should capture the *dynamics* of WIVCs. The ABM method fits well with this requirement.

3.1 SKIN as a base for the IAMRRI model

As described in the introduction, the choice of the SKIN model as a base for the IAMRRI model was founded on a screening/review of 1864 publications. The number of publications were carefully reduced through a multistep screening procedure. This left us with 383 publications that could be relevant for inclusion. These were further reduced as illustrated in **figure 1**. The remaining 6 publications were evaluated based technical, relevance, adaptability, track record, and commensurability merits. As a result of these evaluations, we chose the SKIN model as a base for the IAMRRI model.

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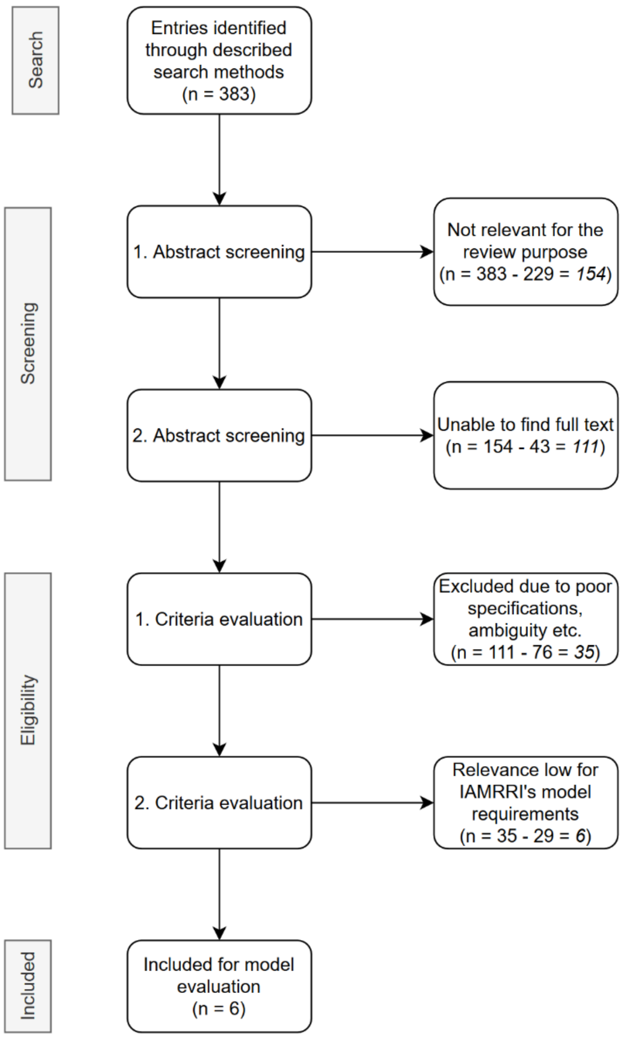

Fig. 6. Review process flowchart

SKIN is a recognized model for studying innovation networks, well documented and tested in various contexts, and has been actively used in policy-oriented research (Ahrweiler, 2017; e.g., Ahrweiler et al., 2015; Gilbert et al., 2018). SKIN is open-source and has a strong and vibrant community, something which has enabled the model to remain current on recent theoretical developments which is impressive given its long history. The basic elements of SKIN such as "kenes" (the set of competences and knowledge an organization possesses), market mechanisms and innovation processes are immediately useful for studying innovation value chains. The original SKIN model is briefly described here. However, the main value proposition of this paper is its adaptations and extensions. Therefore, due to space limitations, we refer to the extensive literature on the base SKIN model for more details on its mechanisms.

Fundamentally, SKIN is an agent-based model of innovation networks in knowledge-intensive industries grounded in empirical research and theoretical frameworks from innovation economics and economic sociology. The agents in SKIN represent

Are JENSEN, Evgueni VINOGRADOV, Nhien NGUYEN
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innovative firms who try to sell their newly developed products to other agents and end users but who also must buy raw materials or more sophisticated inputs from other agents (or material suppliers) to produce their outputs. The model has a representation of the knowledge dynamics in and between the firms. Each firm tries to improve its innovation performance and its sales by improving its knowledge base through adaptation to user needs, incremental or radical learning, and co-operation and networking with other agents.

For thorough descriptions of the SKIN model, we refer to papers dedicated to the topic (Ahrweiler, 2017; Ahrweiler et al., 2011a; Gilbert et al., 2007, 2001; Pyka et al., 2007). When explaining the adaptations and extensions we refer to mechanisms in the base SKIN model.

4 Description of IAMRRI extensions

In this section we describe extensions to the SKIN model so that it will fit the aim of the IAMRRI project. First, we describe the concepts introduced in the adaptations, then we describe the `flow' of the model. The flowcharts presented in **Figures 2** and **3** are useful companions throughout this section.

There are 3 major thematic area s where extensions are suggested: the introduction of a double industry model (to allow for knowledge transfer dynamics between industries through broker agents); RRI (as to examine the effects of RRI on IVCs and resulting innovation networks); and IVCs (allowing for complex innovation value chains). To provide for these thematic extensions, some adjustments must be performed to the model and agent initialization (representing the starting conditions, the agents in the model, and the surrounding environment). **Figure 2** below provides an overview of the base SKIN model and these adjustments.

In base SKIN an agent (a firm) is, during the creation of the model, given one of two levels of resources—high or low, are provided with a (semi)random knowledge base (encapsulated in a ‘kene’), and are tasked with creating an ‘innovation hypothesis’ which represents a product idea. This idea is created based on the innovation hypothesis. When the innovation hypothesis has been created, the firm creates an ‘advertisement.’ This advertisement can be understood as a signal to other organizations that will be read when other organizations are searching for partners for partnerships in the future. The third and last phase of the agent initialization starts with when the agents produce a good based on the innovation hypothesis, and then adjust their expertise upwards as they have gained experience in producing the specific product. With the initialization over, the model starts, and firms take part in the market and adjust their behaviour according to market feedback.

Are JENSEN, Evgueni VINOGRADOV, Nhien NGUYEN

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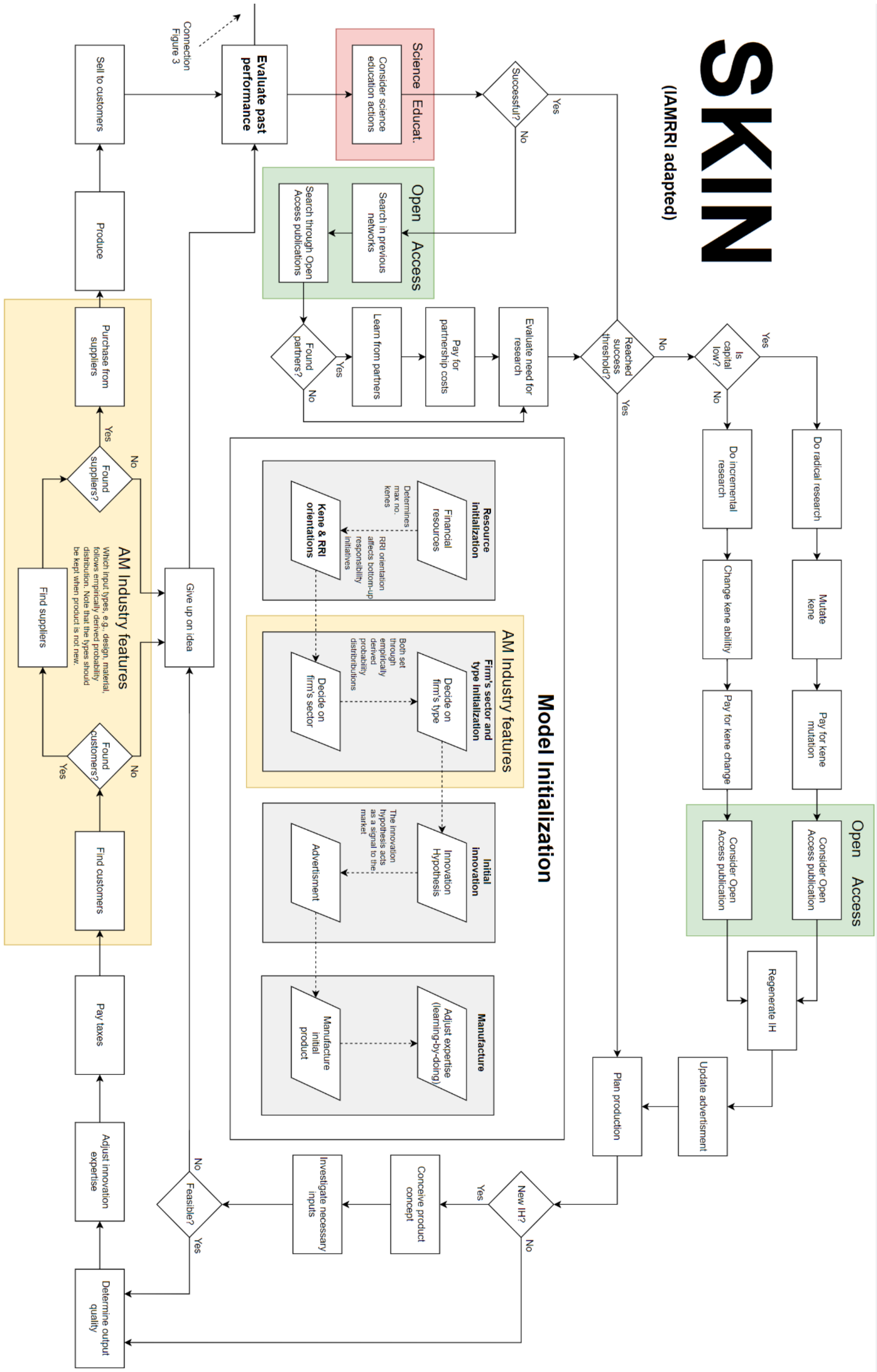

Fig. 7. The SKIN model extended with IAMRRI features.

Are JENSEN, Evgueni VINOGRADOV, Nhien NGUYEN
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In IAMRRI SKIN, agents are also assigned to types common in the AM industry (e.g., software provider, AM material producer). Each agent is given a set of 4 RRI variables with (semi)random values reflecting the mean differences between the types of agents. Kenes are distributed by considering the agent type and the role the agent may play in an IVC.

With these changes to the initialization in mind, we can proceed to describing the three thematic extensions: the double industry model, RRI, and IVCs.

4.2 RRI: Societal Benefits, Ethics, Science Education, Open Access, Funding, Governance, And Public Engagement

In this section we describe several extensions that must be considered together to understand the extension's underpinning logic. The section describes an interplay between organizations taking societal responsibility themselves (in essence 'bottom-up' RRI) and thereby internalize externalities or costs that does not yield them immediate benefit, delayed positive effects of this internalization, and the role of public funding as a catalyst or inhibitor in this process (in essence 'top-down' RRI). Figure 3 illustrates the extensions of the original SKIN model.

The model focuses on four dimensions of RRI: open access, public engagement, ethics, and science education. These 4 RRI keys are modelled as 4 respective variables for each agent. These RRI variables have values ranging between 0 and 1, where 0 means that the agent is not concerned with the particular RRI aspect at all, whereas 1 means that the agent weights this RRI key to the maximum in decision processes involving RRI.

As described below, RRI values for individual agents may change over time. This means that average RRI key for a particular type of agents vary and the new agents appearing during the model run will get initial values that are correlated to the current average for the type.

4.2.1 Learning RRI keys

We model RRI key value changes through the following mechanisms:

First, when an agent is involved into a network or IVC where the average RRI value (of any of the 4 RRI keys) for all partners is higher than his own, the agents RRI key value increases to the level between his own value and the average value for the network. This increase may be conditioned on the results of networking (negative effect, decrease in RRI values) when networking results is positive resultant and positive when results are positive.

Second, under certain scenarios, the exogenous regulators may set a minimum level for certain RRI key (mimicking the impact of RRI key "governance", or the consumers/end-users may require some minimum level). In this case, the firms are

Are JENSEN, Evgueni VINOGRADOV, Nhien NGUYEN
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forced to increase their RRI values gradually. The firms unable to reach the required minimum level are first blocked from networks and then dissolved.

4.2.2 Societal benefits

It is important to conceptualize and define societal benefits so that we can explain how we intend to measure it in the model. We take societal benefit to mean impacts on society that are beneficial in their very nature. Two examples of this provided by the industrial partners in the IAMRRI project are medical implant that help patients in ways that conventional approaches cannot and automotive parts that can drastically reduce the harm to pedestrians in case of a car crash. From this understanding and empirical data collected during the project there are four obvious ways as to how societal benefits manifest themselves: (1) through market demand of products that are more beneficial to society, (2) through AM organizations taking upon themselves to do good in society, manifesting itself through a higher likelihood of wanting to participate in such projects, placing emphasis on CSO (civil society organization) involvement, and a higher likelihood of withdrawing from an IVC if the generated or developed idea turns out to not be beneficial to society or even detrimental to society—this can be thought of us a bottom-up driving force for RRI, (3) an increased likelihood of receiving funding from the public sources if one is attempting to develop innovations that are beneficial to society or receiving more resources and/or on better terms, and (4) through an increased number of youth and students willing to become part of the AM workforce as they see that the AM industry are producing tangible results that are beneficial to society as a whole.

4.2.3 Ethics

Organizations may, due to strategic or simply altruistic reasons, decide to accept higher levels of risk and lower levels of potential profits if they come to understand that their products will likely have more than usual societal benefits. For example, a firm inventing a technology that may lead to medical implants that bring benefits to patients that are not helped by existing technologies--such as one case from our industrial partners—may take it upon themselves to bear the opportunity costs associated with investing in an innovation process that have higher risks and potentially lower profits. If done altruistically, this is simply done as the organization acts according to their established responsibility to society. If done strategically, it may be due to wanting to appear responsible or expectations of future market demands. The behaviour will likely be the same. While this may lead to more products that can help such patients, it may also lead to financial distress of the firm in question, especially if they are in a vulnerable financial situation. If more societally beneficial products are brought to market, it will likely increase the perception of AM in the society. In that sense, taking this risk represents an internalization of the externality of profitability at the cost of societal benefit.

4.2.4 Science education

As with organizationally ethical behaviour, some agents may take it upon themselves to encourage youth and students to learn more about AM, or even begin this knowledge transfer themselves. This can also be considered an internalization of the externality of lacking a stable labour pool in the AM industry. Since the industry is still young, there is a chicken-and-egg problem where there is still hesitation among students whether a career in AM is a good option, and at the same that hesitation is itself limiting the attractiveness of the industry since it itself cannot grow without a growing labour pool. By educating youths and students about AM, it is likely that more of them will be aware of the benefits of AM and therefore either become more conscious consumers of AM products or undertake an education that allows them to work in the AM industry. In short, the organization can take it upon themselves to do science education at little immediate benefit and at some cost, but the whole industry can benefit from this in the future.

4.2.5 Open access

The base SKIN model does not support any functionality for open access publications. It is important to note that not all organizations are in a position, or are likely, to publish open access. This may be due to the nature of the R&D efforts—R&D in a design company will likely entail a very different process than R&D in an AM technology company. Whereas the latter's R&D efforts are more likely to lead to tangible results that are more publication friendly, the former may be and harder to translate into an open access publication. Since R&D entails costs, the agents have reduced their financial holdings during the R&D process. Therefore, the first step is to check their holdings to ascertain whether they are in a position to afford publishing open access. If the answer is no, the open access publication consideration is terminated. If the agent can afford to publish open access, the agent will weigh their ethics and open access orientation and decide on whether to publish. While the weights have a strong effect on this decision, there is also an element of randomness to the decision, representing other factors influencing the decision maker. If the decision is negative, the publication consideration is terminated. If the decision is positive, the publication takes place, and the agent pays the open access fee.

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4.2.6 Funding

A common policy measure for avoiding negative externalities from industry are coercive pressures in the form of regulations (and associated fines in cases of non-compliance). Another policy measure is supporting industry actors that are doing the right thing. While this practice may be controversial, e.g., one might disagree that policy makers support organizations that would act to societies benefit due to profit motives alone, in some cases the profit motives are not present, at least not for the individual firm. In such cases, policies may be put in place to partially, or fully, internalize the externality on behalf of the organization attempting to do the right thing. For example, policy makers can mandate that public procurement processes should give a higher score to firms choosing to only use ethically sourced products, or firms that encourage gender balance in their work force. If this becomes common place and a societal norm, private industry may start to make the same demands. For example, many large institutional investors (such as the Government Pension Fund of Norway) actively pursue a policy of “ethical investing”. Funding in such instances can be seen as both a ‘top-down’ RRI measure, but it can possibly also be considered as a catalyst of the bottom-up efforts presented above. This outcome is not obvious and ought to be examined in the model.

4.2.7 Governance

We suggest a simple mechanism for governance only related to regulations and public reactions. The latter is an expanded understanding of the term governance inspired by Schlaile et al. (2018) but has similar effects in that the public can react by boycotts, seeking prohibitive injunctions, and similar. While we do not make a hard distinction between the two, we note that involvement by CSO at the Idea Generation phase will lower the likelihood of any adverse governance effects at this stage. This represents an advantage of involving CSO during the early phase of the IVC that does not manifest itself until later.

4.2.8 Public engagement

Public engagement refers to the inclusion of multi-stakeholder in the research and innovation process. We understand that public engagement works through two mechanisms in the IAMRRI model: (1) CSOs involvement to represent society’s interests in the IVC; and (2) market effects due to providing society with societally beneficial innovations. In this section we describe the first mechanism, while the second is described in the section on consumer markets effects in the model. In addition, a study using the SKIN model to explore university-industry links has shown that having universities in the co-operating population of actors raises the competence

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level of the whole population and increases innovation diffusion in terms of quantity and speed (Ahrweiler et al., 2011b p.218).

We suggest that CSOs act as ‘guardians’ against potential societally detrimental effects that are tied to innovation ideas. Examples of this could be products that, while technically feasible, may run afoul of societal expectations and considerations. We suggest that, if involving the public at an early stage, the idea will be less likely to invoke reactions from the government or the public.

For the model implementation, we suggest implementing a ‘veiled’ boolean variable representing societally detrimental features of the idea that CSOs are particularly apt at uncovering. While CSO involvement can reduce development speed, their ability to predict adverse as the ones described above during the transition from the Idea Development to Diffusion stage, may make them an important IVC member addition even if it leads to increased short-term costs.

4.3 IVCs

Extending SKIN with IVC support requires several sub-extensions: supporting many organization types, a representation of IVCs, rethinking the duration of steps in the model, and refining parts of the kene concept from the SKIN model so that it supports multiple organization types.

4.3.1 Supporting many organization types

The base SKIN model does not support creating organizations that are different in type. There is some distinction between material providers, producers, and consumers (Gilbert et al., 2007). However, these agents are parts of supply chains, not IVCs. (For a more technical description of how this is implemented in base SKIN, see Gilbert et al. (2001).)

4.3.2 Representing IVCs in the model – adapting SKIN’s network organizations

It is assumed that mechanisms and determinants affecting the structural evolution of networks are industry-specific and strongly dependent on the industry life-cycle stage (Buchmann et al., 2014). Therefore, the networking procedures from the original SKIN are adapted to the AM industry. The base SKIN model supports the notion of network organizations—organizations that are composed of resources pooled from network partners with the aim of inventing and getting a new product on the market – but these network organizations does not take part in an IVC in the traditional sense of the word. Instead, when the network organization are created, the composing organizations’ kenes are put together which will generate an innovation hypothesis which in turn is developed into a product which will be made (assuming it will profitable and inputs for

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the product is found in the market) and sold on the market *all in one turn*. This is not suitable for the IAMRRI model as we rely on studying the different steps in IVCs that take differing amounts of time, e.g., idea iteration loops or warnings issued by CSOs. The existing network implementation, however, is a natural point of departure for implementing the notion of IVCs in a way where participation in the IVC is considered as a collaboration *project*. This allows us to study the performance of the IVC in relation to the organization and allows us to create several IVCs that any given firm can belong to.

4.3.3 Veiled Innovation Hypotheses

One prime reason to start an IVC and invite members to it, is that an idea has been sparked, but the initiating firm (1) lacks the capabilities and abilities to develop it by their own, and (2) parts of the idea is inherently still unknown. Since the IVC is a process that goes through several stages, and possibly through several iterations in each phase, the idea must somehow be developed. In SKIN parlance this can be thought of as the unveiling of an innovation hypothesis. The organizations involved in the IVC phase are likely to influence the nature of the idea as it is developed—in technical term this can entail the IVC members imprinting part of their kene on the innovation hypothesis. (This mechanism is readily adapted from the already existing algorithm for innovation hypothesis generation in the base SKIN model.) Note that once the firm has imprinted part(s) of their kene on the innovation hypothesis, the part is no longer associated with the firm type. The logic behind this ties to that while the idea requires different inputs from different firm types, e.g., design, once the design is in place, the other firms in the IVC does not need to understand how the design came to be—it is simply enough to know how use the design (and this knowledge in turn will naturally be conveyed within the IVC to other members as part of the development). Therefore, an innovation hypothesis that has been developed in part by an AM design company during idea generation does not require the AM design company for, e.g., diffusion. Once all the parts have been 'unveiled' the idea is ready for the next phase. As the idea transitions between phases, so does the innovation hypothesis through adding more features that must be unveiled. This reflects the complexity of an innovation that requires an IVC and the empirical observation that other firm types are required for subsequent IVC phases. Because of this, some of the firms' participation may no longer be required, and they will naturally transition out of the IVC, while others must be found either through remaining members existing networks or through searching for relevant capabilities and abilities in open access publications. If the idea makes it all the way to the diffusion stage, base SKIN mechanisms take over (see description of the three phases below).

Are JENSEN, Evgueni VINOGRADOV, Nhien NGUYEN
DOI: 10.3217/978-3-85125-855-4-12

4.3.4 The IVC stages and timing

The base SKIN model also assumes that an organization's research, prototyping, production, and market related activities can all take place, for a specific product, during one step of the model. Since the IVC process can take several steps and are not necessarily equally long for any given innovation, it is necessary to adapt the SKIN so that innovation processes can take more time than what is currently represented in one step in the SKIN model. The IAMRRI model deals with this issue by letting each step represent a shorter amount of time. Both theoretical publications and input form participants indicates that dividing innovation process into three phases is necessary. These phases are Idea Generation, Product Development, and Innovation Diffusion.

The original SKIN implicitly contains processes of the idea (innovation hypothesis—IH) generation and development in a single step. This process is influenced solely by kenes of firms and IH is randomly generated from the set of available kenes. In the extended version, new IH will be more likely to appear when a new raw material, software or other input is developed on the demand from another firm. Appearance of new IH may be initiated by the actors other than the firms, such as universities, regulating organs, and open innovation sources.

The Product idea development phase is not explicitly presented in the original SKIN model. The extended version suggests that the innovation hypotheses may be developed further in two ways: 1) if the necessary input is absent, the firm owing IH asks other firms to develop this kind of input and 2) if IH is not feasible, the firm may try to adjust it internally or in partnership with, for example, Research Institutes.

In the original SKIN Innovation diffusion means selling to the market depending on costs while demand is essentially fixed. Customers choose the cheapest product or, if the price is equal for several products, the products with highest quality. In the extended version, additional factors influence the product choice. RRI values are inherited by the product from the firms involved into relevant IVC. Customers with relatively high RRI values may choose products that are high on RRI values, even if they are more expensive than alternative products or have lower quality.

Idea generation phase: It is suggested in the modelling literature that creative ideas can be generated locally (within a unit), across different units, or obtained from external sources (Kusiak, 2009). During the idea generation phase a firm of random type may come up with an idea that requires an IVC in order to be developed. In modelling terms, this can be represented as an innovation hypothesis that has hidden parts that can only be unveiled through idea iterations together with IVC partners. This is illustrated in the lower corner of **figure 3** in the box labelled "Generation of incomplete IVC IH". Throughout this section and the next, **figure 3** can be a useful as it illustrates the circular nature of some of the mechanisms explained in the text.

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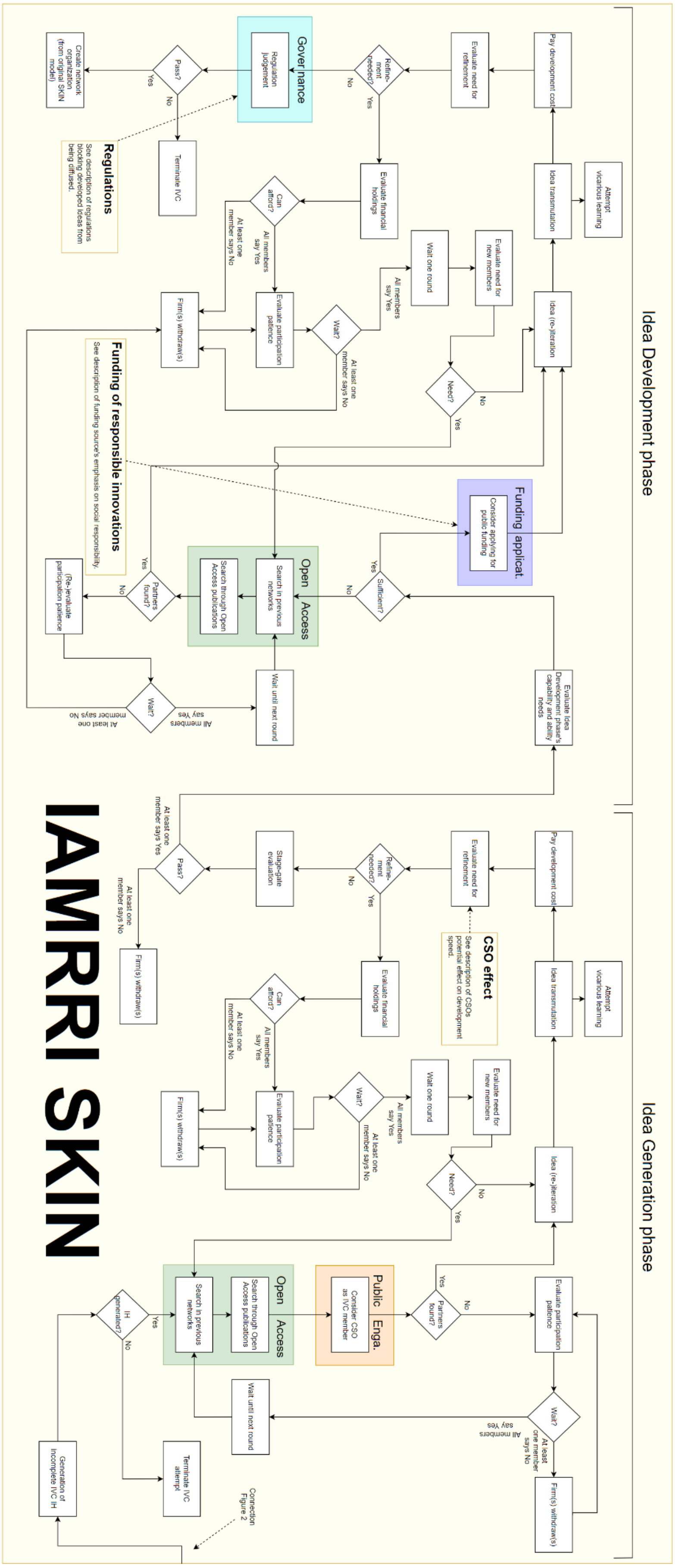

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Fig. 3. IAMRRI's IVC and RRI extensions of the SKIN model

For the agent to start the IVC proper, it must find IVC partners. In base SKIN, one search feature is the firms' previous networks. These networks are, in base SKIN, developed as firms are unable to achieve success in the market with a particular product and therefore attempts to learn from another agent so that they can create a new product that may be more successful. We suggest that this mechanism be modified such that partnerships are still the preferred channel for IVC member search, but that searching through open access publications that signal a particular set of skills. One may assume that open access' primary function is knowledge sharing, but from interviews and workshops with AM stakeholders we came to understand that much of the information contained within AM publications would be prohibitively difficult to make use of oneself.

During this phase, firm preferences come into play. Since both ethics and public engagement are closely tied to the norms and behaviours of AM actors, we suggest that firms' decision to join the IVC are strongly influenced by their Ethical orientation and Public engagement orientation. In addition to these evaluations, the agent will also take financial risk and opportunity cost into consideration.

In cases where not enough partners are found, the partners that have been found, as well as the Idea Generation instigator, will evaluate their participation patience. Their patience will be related to whether firm perceives that ethical and public engagement requirements are met and financial risk and opportunity costs are low. In addition, their patience will be affected by the number of partners in the IVC so that the more partners there are in the IVC the lower the likelihood of leaving. This reasoning is based on group size conformity effects, a well-known effect from social psychology explaining how individuals, in this case those representing their firm in the IVC, are less likely to leave a group if it is above a certain size. In short, this represents a group-think-like effect that makes on second-guess ones one judgement if making a different judgement than the rest of the group (Campbell and Fairey, 1989). This has the potential to create a cascading effect where if one firm leaves, others are more likely to leave. Therefore, we suggest that this is modelled in a cyclical fashion until no more firms are willing to leave. Those firms that are willing to stay, will reduce their patience for each round they chose to stay, so that the longer they have been on hold, the less likely they are to remain. If the IVC is not dissolved after these determinations, the IVC is put on hold until next round of the model.

When the funding decision has been made, the IVC members iterate on the idea. This entails a stochastically determined outcome of unveiling one of the columns of the innovation hypothesis. If they, e.g., find that ideas must be iterated over a long period of time, the likelihood of unveiling a part of the innovation hypothesis would be lower than if ideas quickly transition into the idea development stage. During this iteration phase, agents have the possibility to learn from the other IVC members. Being involved in this idea iteration incurs costs to the agents involved. When learning from each other the partners are more likely to learn from the firms with kenes that are relatively alike their own (Shou and Sun, 2010).

After the idea has been iterated over, in cases where CSOs are involved, the CSO may warn of potential issues that must be dealt with before the IVC should proceed. This represents the ‘guardian’ role CSOs can have if unethical or otherwise socially undesirable ideas are being developed, highlighting the potential drawbacks of involving CSOs. If such a warning is issued, this ensures that the idea must be reiterated over, increasing costs, and possibly leading to IVC members withdrawing from the IVC. The inclusion of CSOs is not without its advantages on the IVC level—it can lower the likelihood of adverse effects in the future (see the next section on the Idea Development phase). This reiteration does not occur only due to CSO warnings: it will also occur if the innovation hypothesis has not been sufficiently unveiled for it to proceed to the idea development phase. In any case, this reiteration is similar in effect to the partner involvement patience evaluation presented earlier.

If the iterations complete and the idea is ready for the next phase, idea development, then the firms will perform a stage-gate evaluation. We suggest a simple mechanism: the agents involved will examine their participation in the idea development phase in much the same way they would any other reiteration as they are described above. If no firms are left after this iteration, the IVC will be terminated. That does not mean that the IVC has been unable to provide any useful outcomes: the increased knowledge among the agents that have participated may lead to other IVC participations at a later stage and can help the agents as they develop their own innovation hypotheses independent of the IVC. While it may seem counter-intuitive that the whole IVC is terminated at this point, it is more reasonable when considering that none of the agents receive any financial gains when participating in the IVC: their primary gain at this stage is the knowledge from idea iteration together with the participating partners.

Idea development phase: For the sake of brevity, we will not explain the search process as it is identical to the one described in the idea generation phase with one exception—there is the opportunity for funding at this stage. Early during the idea development phase, the agents will consider applying for public funding. This is illustrated by the box labelled “Funding applicat.” in figure 3. We suggest a mechanism in which RRI dimensions are weighted so that those ideas that are more RRI oriented are more likely to receive funding. Also, if the IVC members involved CSOs during the idea generation phase and are developing an idea that is inherently socially beneficial, they are more likely to receive funding. This has the consequence of reducing the financial risk going forward, and the likelihood of firms having to withdraw from future

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idea iteration due to financial constraints. Note that this represents an interaction between bottom-up RRI efforts—caring about CSO involvement on the firm level and being concerned with ethics—and top-down efforts—preferring to fund ideas that are more closely aligned to RRI keys and ideals.

Most of the other parts of the idea development phase is identical to the idea generation phase—that is not to say that the same actions occur in the field, but rather that it follows the same circular pattern of iteration, possible refinement, possibly partners leaving, new partners coming into the IVC, then reiteration if sufficient members are found. One important part (besides funding) differs, however, and that is the possibility of regulation or other interventions by either the public, e.g., in forms of prohibitive injunctions to stop sale or diffusion of products, or the government, e.g., the government interprets the idea as going against existing laws or it considers creating new regulations and laws preventing the sale or diffusion of the resulting product or service. The likelihood of this happening is considerably lower if an CSO has been involved at an earlier stage. In other words, the involvement of CSOs at the idea generation phase can lower the likelihood of adverse events in the transition from the idea development phase to the idea diffusion phase.

If the idea development phase is successful, the IVC transitions into the diffusion phase:

Diffusion phase: The diffusion stage in IAMRRI SKIN is similar to the network organization already implemented in base SKIN. The major exception is the requirement of the participating firms already having partnered with each other. We propose that the transition from the Idea Development phase into the Diffusion phase follows the same logic as from the Idea Generation phase to the Idea Development stage. If the necessary agents are found they take part in forming a network organization as described in the base SKIN model. How this transition is done has not yet been determined. This is fertile grounds for research. We suggest that the creation of the network not only hinges on the idea being successfully developed, but also on the feasibility of the product in the market. This feasibility search can readily be coupled with the existing market mechanisms in base SKIN—if any products were attempted bought, but not supplied, in the market during the previous round, a network is more likely formed to handle the diffusion. An experienced SKIN modeler will notice that this seems to be incompatible with the way base SKIN handles how agents behave after not being able to find inputs (they will immediately—in the following round—attempt to produce something else). This is an issue that should also be researched further.

Significant changes to the base SKIN model are summarized in **table 1**.

Are JENSEN, Evgueni VINOGRADOV, Nhien NGUYEN
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Table 1. Brief overview of changes from the original SKIN model

Original SKIN	IAMRRI SKIN
Model initialization	
Single industry.	Double industry.
One to two types of agents.	Max. 9 types of agents, but simplification groupings are suggested.
No RRI.	4 RRI keys assigned to each agent.
Kenes randomly assigned to agents.	Purposeful assignment of Kenes to different types of agents.
IVCs and Veiled Innovation hypothesis	
Innovation hypothesis (IH) is static and readily formed based on single firms' kene, except in network organizations.	In addition to IHs in original SKIN, IHs in IVCs are initially incomplete and developed over time borrowing the missing kene elements from other agents. The innovation idea goes through three stages (idea generation, development, and diffusion; diffusion is similar to the network organization agent 'collective' in original SKIN).
Time frame	
All stages of innovation process performed in one tick. No delays happen.	Innovation processes stretch over time. Innovation idea goes consequently through generation, development, and diffusion phases over multiple ticks. Delays happen.
Networks	
Network organization is created, the composing organizations' kenes are put together, a new innovation hypothesis is developed into a product which will be made and sold on the market *all in one turn.*	Participation in the IVC is considered as a *project* in the firms starting the network organization (networked project).
A firm may participate in only one network at a time.	A firm may participate in multiple network projects at a time (but keeping the network concept from SKIN as a separate concept).
The search for potential network firm partners is limited to those a firm has already had a partnership with in the past.	Firms' can also search partners through open access.

5 Conclusions and Suggestions for Further Research

In this paper we presented extensions to the SKIN model so that it can support the simulation of more than one industry, innovation value chains, and RRI. The model was built based on theoretical as well as empirical insights provided through the IAMRRI project.

While the model represents a step forward on the path to understanding innovation processes, work remains. First, while the model has begun to prove itself in the context

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of additive manufacturing, the question of whether it is generally applicable remains unanswered. Second, while this paper does not show an implementation of the IAMRRI model, such an implementation does exist. However, this implementation is tailored to answer specific research questions in the IAMRRI project. Therefore, some of the extensions described here, specifically those in the market section of the model, have yet to be implemented. Implementing the full model and releasing it as an open-source project would benefit modellers interested in innovation networks, innovation value chains, industry dynamics, and RRI who could then use the model to test specific theories and hypothesis. Third, sections of the IAMRRI model are underdeveloped. For example, the diffusion phase of the innovation value chain is not able to deal with more complex intellectual property issues. We know from empirical data that intellectual property rights issues can have large ramifications for the market diffusion of technologies developed inside of innovation value chains.

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