Cyclical Interaction at the Science-Industry Interface,
theoretical foundations and implementation examples

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Executive Summary

Tomorrow's quality of life is determined by today's innovation power. Therefore, greater insight into innovation processes and how they can be better facilitated is of major strategic value to governments, business* organizations and knowledge institutes.

Changes in society today are being driven by both revolutionary scientific and technological discoveries, and the development of new business models for private and public organizations. The result is a dynamic society that is undergoing massive transformation – on all scales, and at all levels. To get a better understanding of the complex processes behind those transformations, an integrated framework is necessary: one that leads to a *system-based* perspective of innovation, and facilitates effective communication between the different stakeholders. The Cyclic Innovation Model (CIM) is proposed as such a framework.

In CIM, an innovation-driven society is described by coupled cycles, each cycle representing a network of forward and backward interaction processes across science and industry. These coupled cycles form a never-ending loop, and recognize the innovation processes in all sectors of society.

CIM argues that future organizations will be increasingly guided by human needs and concerns, leading to service-driven goals and boundary-crossing models in both science and industry; it provides insight into the (re)design of these models for *sustainable* policy-making, business development and multidisciplinary research.

CIM concludes that the competitiveness of a nation is increasingly determined by its ability to integrate innovation processes within and across all cycles of the innovation system.

** Here, 'business' includes both the manufacturing and service industries.*

Introduction

Nowadays, changes in society take place so quickly that it is difficult to get a proper grip on the pace of new developments. On the one hand, we see far-reaching social and economic changes causing existing solutions to become less effective, or even obsolete. On the other, we see revolutionary discoveries in science and technology inspiring new solutions, and creating new opportunities (figure 1). In other words, changes in society accelerate the creation of new knowledge (societal pull), and new knowledge drives changes in society (knowledge push). Innovation is a *cyclic* process[1].

Moving away from the steady state concept
Figure 1 schematically illustrates the cyclic interaction of the two sources ('nodes') of innovation: knowledge and business[2]. In this model, the involved push and pull forces continuously challenge one other, creating a vibrating socio-economic system (comparable with a vibrating mass-spring system in physics). In such an innovation-driven system, balances do not exist. On the contrary, nett forces exist in the system, and these continuously drive the accelerations. Moreover, in this system, human labor cannot merely be positioned as a *production* factor; the contribution that human beings make should be seen increasingly as the *innovation* factor. The above involves a fundamental change in the way we look at today's socio-economic system. Now, the emphasis is on dynamics, innovation and sustainability. Static, production-focused, neoclassic models provide an outdated description of the reality. This paper illuminates the necessity of introducing innovation-driven, socio-economic models consisting of coupled processes in different subsystems. The dynamics of these subsystems are characterized by potential energy (knowledge) and kinetic energy (business), together with coupling losses (institutional mismatches) and friction losses (process inefficiencies). Two topical examples of dynamic subsystems having huge societal impact are the industry-driven information and communication sector, and the science-driven biotechnology sector.

Moving away from the pipeline concept
Looking at the huge complexity of the interactive processes in an innovation-driven socio-economic system, one can see that an integrated framework is needed to bring order to the apparent chaos, and to reveal cohesion between the many different developments taking place in innovation, i.e. a *systems approach* should be adopted.

In policy-making, frameworks have been introduced and implemented that describe the innovation process as a serial, relay-type path. This family of frameworks is generally referred to as the 'linear innovation model' [1]. Nowadays, however, it is increasingly realized that linear innovation policies easily lead to segmentation, i.e. many sequential tasks being carried out by independently operating organizations. In this paper, a more realistic assessment of the innovation process is proposed, taking into account that innovation may start at many different crossroads, and *feedback* interactions are as important as feedforward ones (figure 1). Traditional

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[1] A cycle represents a sequence of related processes that continuously repeats itself with new boundary conditions. In practice, cycles occur on different levels, and at different scales.
[2] Here, 'knowledge' refers to both explicit and implicit knowledge, and 'business' includes both the manufacturing and service industries.

institutions may require a complete redesign in order to better facilitate the intricate interaction processes at the roots of innovation [2].

Cyclic Interactions

Figure 2 presents a more detailed version of the interactions occurring in the system innovation cycle. It reveals that the interaction paths in figure 1 represent multichannel processes: each path represents a 'one-to-many' distribution process and a 'many-to-one' collection process between knowledge creation and business generation. Let us examine those interaction processes in more detail. This is illustrated in figure 3.

The feedforward path in the innovation cycle shows that one field of knowledge can contribute to many application sectors[3] (one-to-many), i.e. knowledge *dissemination* (figure 3, upper left). The feedforward path also shows that many different fields of knowledge can contribute to the progress in one application sector (many-to-one), i.e. knowledge *integration* (figure 3, upper right). Similarly, the feedback path shows that ambitious goals in one application sector must be translated into specific research topics for each field of knowledge involved (one-to-many), i.e. *decomposition* in the innovation cycle (figure 3, lower left). This leads to an application-driven, multidisciplinary research program. Hence, when setting up multidisciplinary research programs for a specific (potential) application, the question should not be 'who would like to join?' but rather 'who do we need?'. The feedback path also shows that the predicted consequences of a specific knowledge discovery for different applications can lead to important steering information for the processes in the involved field of knowledge (many-to-one), i.e. *reflection*[4] in the innovation cycle (figure 3, lower right). Many innovation policies stress the need for knowledge dissemination. Figure 3 shows that this view is too limited: knowledge dissemination is just one of four important processes in innovation.

Electronic communication is a great facilitator for these 'network processes'; the Internet is predominantly suited to unlimited, one-to-many and many-to-one communication. The cyclic, multidimensional interactions underlying innovation and the unique capabilities of (wireless) broadband electronic communication strengthen one another; this synergy explains many of the novel knowledge and business developments in today's network economy.

To summarize, the cyclic processes point to four different types of interaction within the system innovation cycle (figures 2 and 3). Two of these occur in the forward path: *dissemination* (one-to-many) and *integration* (many-to-one); the other two occur in the feedback path: *decomposition* (one-to-many) and *reflection* (many-to-one). These cyclic interactions can occur with varying degrees of intensity:

- *dissemination* ranges from 'uncommitted diffusion' to 'dedicated transfer'
- *integration* ranges from 'loose coupling' to 'excessive fusion'

[3] Here, 'application' refers to the utilization of new knowledge in existing business, or existing knowledge in new business, or both.
[4] 'Reflection' refers to responses from society to the knowledge-creating activities (feedback) in terms of needs and concerns.

- *decomposition* ranges from 'making a generic subdivision' to 'prescribing well-defined modules'

- *reflection* ranges from 'signaling needs' to 'expressing concerns'.

In a system-based innovation cycle, dissemination, integration, decomposition and reflection processes occur simultaneously, and all (should) influence one another. These processes can be real, augmented-real or virtual. This explains the immense complexity of innovation today, and leads to an important observation: national governments should *not* attempt to design detailed roadmaps for the boosting of innovation [3].

We have used figures 2 and 3 to visualize the multichannel interactions between knowledge creation and business generation. We will now look at these processes once more, this time using a matrix (or spreadsheet) presentation. This is visualized in figure 4. The processes in one column of the 'knowledge-application matrix' represent disciplinary research in one field of knowledge. The processes in one row represent cross-disciplinary research for one application sector. Figure 4 shows that the complex 'one-to-many' and 'many-to-one' interactions (both feedforward and feedback) can be arranged in an interaction matrix, revealing the vertical and horizontal processes in system-based innovation. Knowledge fields such as ICT are critical for many different applications. Complex application sectors such as utilities, transport, health care, public safety, environmental sustainability etc., require knowledge from many different fields. Note that the vertical processes in the columns of figure 4 represent the left-hand node in figure 1, and that the horizontal processes in the rows of figure 4 represent the right-hand node in figure 1.

A matrix provides the most general presentation of the interactions between two different communities (figure 4).

CIM: a never-ending loop of coupled innovation cycles

For practical implementation, the system-based innovation cycle must be detailed. Here, we will distinguish two nodes for knowledge creation (knowledge-creating nodes):

- disciplinary science
- technological research

and two nodes for business generation (business-generating nodes):

- development of products
- building of services

This double subdivision leads to a detailed version of figure 1: the Cyclic Innovation Model (CIM). The result is visualized in figure 5. Figure 5 shows the cyclic interaction between the four nodes of CIM, leading to four, coupled innovation cycles:

- the *fundamental science cycle,* for the creation of cross-disciplinary process models (lower left-hand side);
- the *strategic knowledge cycle,* for the creation of cross-disciplinary technology (upper left-hand side);
- the *integrated engineering cycle*, for the generation of cross-technology products (upper right-hand side);
- the *customized market cycle*, for the generation of cross-product services (lower right-hand side).

Note from figure 5 that each node functions in two cycles, allowing strong coupling between two neighboring cycles. Note also that in today's market cycle, products are surrounded by services, and services are enabled by products.

> CIM does not represent sequential *steps* but coupled *cycles*; it does not represent a finite *chain* but an endless *loop* (figure 5).

In the new society, cross-product service provision plays a key role and the fundamental science cycle (lower left-hand cycle in figure 5) should be used to increase the insight in the complex processes involved: *this is the weakest link in today's national innovation systems*. Considering the strong growth of customized services (business-to-business as well as business-to-consumer), the multidisciplinary models in the science cycle should not only contain technical and economic disciplines, but also specialized knowledge from social sciences and the humanities[5]. Successful integration of this wide variety of scientific building blocks will be a major challenge for the science community [4].

> Future society will be increasingly driven by human needs and concerns. This explains the spectacular growth of today's service industry. Multidisciplinary research in the fundamental science cycle should therefore particularly aim at improving insight into the huge complexity of service-driven processes (systems approach).

To summarize, CIM shows innovation processes occurring in a never-ending loop (outer loop) of four, coupled innovation cycles (inner loops), all characterized by multichannel feedforward and feedback interaction processes. In a well-functioning innovation system, the individual cycles continuously strengthen one another, creating synergy within the outer loop. This means that governments should replace their traditional science, technology and industry policies with *one boundary-crossing innovation policy*, i.e. they should adopt a systems approach to policy-making. With such a fully integrated innovation policy, manufacturing companies must be seen as industrial suppliers to service providers. Industrial products are then seen as part of a much 'bigger picture' – they become *building blocks* (enabling modules) for socio-economic services: a shift from selling products to fulfilling needs. Rapid changes in society lead to rapid changes in human needs and concerns, and vice versa. The service sector must keep up with these changes, which leads once again to new demands being placed on the manufacturing industry. One of many examples is the food industry. The traditional way of selling a basic choice of food

[5] Consumer emotion (human needs and concerns) should therefore become an integral part of future scientific modeling.

products is being replaced by the provision of customized food *services*[6]. These services take into account the increasingly refined wishes of individuals with respect to smell, taste and texture (enjoyment aspect), reliable information about the ingredients, processing methods and storage life (safety aspect), and, increasingly, to nutritional values (health aspect).

Just as in figure 4, the complex ‘one-to-many’ and ‘many-to-one’ interactions in each innovation cycle can be visualized with the aid of a matrix. This leads to a network presentation of CIM with four coupled interaction matrices (figure 6). Note that the vertical processes in the left and right columns of figure 6 represent the left and right nodes in figure 5, respectively; and that the horizontal processes in the upper and lower rows of figure 6 represent the upper and lower nodes of figure 5, respectively. Note also that rows and columns always appear in two neighboring cycles, showing the importance of cross-cyclic interaction. This important property is highlighted in figure 7.

Figure 7 shows that the disciplinary science columns (left), and product development columns (right), should be connected by the technological research rows (upper), and service provision rows (lower), *like the warp and weft in textiles*. This also leads to new opportunities for increased cohesion in society.

> In CIM, technological research and service provision have been positioned as the driving processes behind the society of the future (‘horizontalization’). Both of these ‘horizontal processes’ are interconnected through the ‘vertical processes’ in disciplinary science and product development, like the warp and weft in textiles (figure 7).

Different dimensions of CIM

CIM: clarifying the interactions in an innovation process
CIM reveals the huge complexity of the *interactions* in the total innovation process. However, by presenting the total process in terms of four coupled cycles (fundamental science, strategic knowledge, integrated engineering, customized market), and by presenting the large number of interactions within each cycle in terms of a goal-driven matrix-network with rows and columns -*the building blocks in a cycle*- this complexity is reduced and all interaction processes can be more easily assessed. This is particularly true if subcycles are introduced, showing interactions at a more detailed level.

CIM: combining building blocks and crossing boundaries
The proposed innovation framework emphasizes that system-based innovation can be realized by introducing *new building blocks* to an existing combination, or by using existing building blocks in a *new combination*, or both. The quality of an innovation result is determined by the choice and quality of the individual knowledge and business building blocks, as well as the quality of the integration process. This integration process is crucial, and determines the ultimate performance of the combination. It must occur within, and across, all innovation cycles. This requires the removal of dividing walls between all sectors of society, most dividing walls being caused by

[6] In the food industry, the shift from products to services is accelerated by the trend to depart from traditional family cooking.

segmented institutions and differences in organizational culture. It means the extensive decompartmentalization of economies, requiring the demolition of artificial barriers between ‘columns’ and ‘rows’, leading to a *cross-cyclic economy* with global cross-discipline, cross-technology, cross-product and cross-service processes.

> Knowledge creation and business innovation can be realized by introducing new building blocks to an existing combination, or by using existing building blocks in a new combination, or both.

CIM: a framework for cross-cyclic roadmapping

Cross-cyclic roadmapping assists in establishing the building blocks and business partners needed to successfully realize new concepts. Figure 8 shows one result of such a process. Starting with the business specifications of a new service (lower right row), the various missing product segments that facilitate the realization of this new service are indicated (lower right and upper right column elements). Next, the technology branches that allow the development of these newly-required products are specified (upper right and upper left row elements). In addition, the scientific disciplines needed to underpin the research for the missing technologies are identified (upper left column elements). Finally, the scientific disciplines for the development of the multidisciplinary scientific model of the new service provision process are indicated (lower left column elements). Figure 8 therefore visualizes the output of a four-fold decomposition exercise, producing an integrated overview of the missing knowledge (left) and business building blocks (right). The result may be the complex distribution of many diverse building blocks (marked intersections in figure 8), revealing the necessity for priority setting.

The next strategic issue to be considered is, therefore, involving the best partners from the (global) knowledge and business communities, i.e. who do we need? The proposed building blocks of all involved partners must be synthesized using an integration process across all innovation cycles. This requires full compatibility between all involved building blocks! In practice, this analysis-synthesis sequence is iterative, defining a cross-cyclic roadmapping process that requires the development of various new (or improved) knowledge and business building blocks (figures 9 and 10). Today, innovative business development by cross-cyclic roadmapping is applicable to all public utilities and emerging services, e.g. energy, water, food, health, safety, mobility, transport, information, telecommunication, financial, legal, etc.

CIM: a framework for sustainable employment

In the context of employment, CIM formulates an integrated framework of vertical and horizontal building blocks in terms of goal-driven processes, human tasks and matching competencies. CIM shows that scenarios related to work should be based on an analysis of these building blocks within each cycle, taking into account the strong intercyclic relationships. The result is an iterative approach, yielding a wide-angle perspective of ‘the future of work’.

CIM: tracing process deficiencies in the innovation loop

Successful innovation requires a seamless flow of actions, reactions and transactions within, and between, the four innovation cycles. Deficiencies in the system caused by intracyclic or intercyclic barriers and mismatches lead to friction and delays. The result is lack of synergy between the cycles in the innovation loop. Even just one malfunctioning cycle creates a bottleneck in the innovation loop, and the processes are slowed down or stopped altogether.

Therefore, sustainable innovation requires balanced investment in the quality of *all four* cycles, leading to a balanced (national) innovation policy.

> If service provision becomes the driving process behind the society of the future, CIM indicates that work will involve into a cyclic system of interrelated human activities with the objective to 'serve society and its environment'.

To summarize, CIM can be characterized as an integrated framework that:

- describes an innovation-driven society by coupled cycles to form a sustainable, never-ending loop.
- demonstrates the need for balanced investment in the quality of all four innovation cycles.
- increases the sense of urgency to decompartmentalize society by removing artificial barriers between vertical and horizontal processes.
- assists with the design of boundary-crossing 'business models' for future scientific, industrial and governmental organizations (cross-cyclic roadmapping).
- points at new opportunities to assess the future of work.
- concludes that the competitiveness of a nation is determined by its ability to integrate innovation processes within and across all cycles of the innovation system.

Examples

During the presentation, the added-value of CIM in system-based innovation will be illustrated using three examples:

1. Multidisciplinary research for technological innovation at Delft University of Technology, The Netherlands: combining disciplinary columns into multidisciplinary technology rows in the strategic knowledge cycle (upper left-hand innovation cycle).

2. Technological Top Institutes, a science-industry cooperation in The Netherlands for technological innovation: interaction between the strategic knowledge and engineering cycles via the technology rows (combining upper left-hand and upper right-hand innovation cycles).

3. Sustainable Airport Cities of the New Economy, design of an international science-industry-government program that integrates all four innovation cycles.

For a complete treatise on CIM, please refer to Berkhout, A.J., 2000, 'The Dynamic Role of Knowledge in Innovation: an integrated framework of cyclic networks for the assessment of technological change and sustainable growth'.

Conclusion

The principal role of governments in innovation is to *facilitate* the four basic interaction processes within each innovation cycle (intracyclic interaction), and *stimulate* interaction between the different innovation cycles (intercyclic interaction). National science, technology and industry policies should therefore be combined into one integrated innovation policy.
CIM shows that within this integrated innovation policy, particular attention should be paid to the fundamental science cycle, the weakest link in today's national innovation systems.

Reference

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