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How Do Intelligent Goods Shape Closed-Loop Systems?

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SUMMARY

Disruptive technologies can increase the intelligence of goods and revitalize business models in the circular economy. Applying an industrial ecology perspective, this article discusses how intelligent goods can boost the sustainability of industrial ecosystems. North American and European cases highlight how business model innovators can utilize goods-related information to develop more competitive closed-loop systems. The authors identify three archetypes of closed-loop systems—inner circles, decentralized systems, and open systems—and delineate how they leverage information resources for collaboration. This study advances the understanding of closed-loop systems in the circular economy, which is more dependent than ever on digital platforms.

KEYWORDS: circular economy, environmental protection, green manufacturing

A growing body of research has drawn attention to value creation in closed-loop industrial systems[1] because environmental concerns are pressuring organizations across industries to rethink their business models.[2] In addition, the ownership, recycling, and sharing of material resources are taking new forms with the rise of the circular economy. Closing industrial loops by making better use of raw materials and by turning waste into energy and components for refurbished goods contributes to environmental sustainability and provides new business opportunities for industrial actors. For example, conflating ownership of goods with ownership of the information and data in goods opens up the space for novel business models in smart manufacturing. Consider our findings from Canadian supply chains: the virtuous cycles of a circular economy are built on both green production and

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green supply chains.[3] Furthermore, the findings indicate how tracking the provenance, sustainability, and ownership of goods and materials as well as ensuring the profitability of supply chain actors are crucial activities. Firms are now more dependent on resource and capital efficiencies because customers are paying more attention than ever to the provenance of goods and the ways that firms buy or license replacements. The circular pathway is a more sustainable way for a society to continue prospering without exhausting primary materials and energy. It is made possible by reducing waste in production and consumption of products, especially through closed-loop recycling. To illustrate, more than 80% of all copper ever mined is still in circulation today.[4]

Goods are increasingly equipped with computing and data processing capacities that enable handling and storing of information about their real-time condition, location, operation, use, history, and the surrounding system in which they are used. This "embedded intelligence" enabled by information software and hardware transforms products into active nodes of new value-creating systems. Moreover, the rise of the circular economy transforms goods-focused businesses into service- and platform-focused businesses; it is changing the ways in which information sharing and market transactions take place. Although the increasing intelligence of goods, the resulting information intensity of services, and the impending shift to digital platform-enabled transactions[5] have all attracted considerable research attention, there is little empirical work on the collaborative practices of utilizing information resources and objects in business ecosystems of the circular economy. This is a critical gap in the knowledge, because firms in technology-enabled business ecosystems need to play an active role for the circular model to work. Just as the use of raw materials is important for production, innovative firms must develop new industrial systems and practices for sharing information and make use of the information related to circulated materials and products. For closed-loop value creation to be productive and sustainable, it is necessary to widen the consumption of goods by extending their longevity and by reconsidering ownership issues. For such goals, information about the goods plays an essential role.

To fill this gap in the knowledge, we explore *the ways in which the intelligence of goods influences closed-loop ecosystems*. In so doing, we extend the discussion of firms' competitive behaviors by adopting the perspective of industrial ecology to illustrate how companies collaboratively utilize resources and capabilities within their networks based on their context-specific needs.[6] The growing intelligence of goods as well as the growing autonomy of programmable devices are generating novel constellations of value creation and capture.

Based on our empirical research, we conceptualize three archetypes of closed-loop systems as inner circles, decentralized systems, and open systems. These archetypal systems exemplify different approaches to collaboration, the management of information resources, and innovation for sustainable recycling. Moreover, these circular models utilize disruptive technologies in their business models and highlight the role of intelligent goods in creating value with services in which the value is not measured or experienced in terms of physical assets. In so doing, our study highlights the role of intelligent goods in shaping closed-loop systems.

For closed-loop systems to sustain themselves, firms must step away from focusing exclusively on the flow of goods and instead reconsider their roles, responsibilities, and complementarities by using goods-related intelligence in the new industrial systems. This shift in focus is increasingly important considering how the traditional thinking of markets, assets, and value propositions—which draws upon the resource-based view of competition—may lack the emphasis on reducing inexhaustible material and energy flows. For example, Kenneth Boulding vividly depicted this traditional thinking as the "cowboy economy" to underline the reliance on continuous supply of new material resources.[7] It is reasonable to suggest that material intelligence and more effective management of information related to goods will contribute to the rise of the circular economy through a healthier balance of material and energy flows.[8] The circular economy does not only mean corporate sustainability or green strategies. It also requires the creation of trust among business partners and the development of new practices of sharing information and utilizing resources by plugging potential structural holes[9] in the emerging business ecosystems.

How Does the Intelligence of Goods Affect Closed-Loop Ecosystems?

To manage intelligent non-durable, durable, and capital goods, fluent information exchange between nodes and organizations in diverse business ecosystems is crucial. While technological disruptions of information exchange create opportunities for value creation and capture, they can also create structural holes in existing and emerging industrial systems. That is, new capability and information gaps arise where the current ways of exchanging information among the actors fail to meet the actors' evolving business needs. A new actor may assume an integrative role to close the gap, and, thus, subsequently plug the structural hole. Therefore, a structural hole can also be considered a source of innovation as third-party actors[10] become aware of alternative ways of thinking and behaving in industrial systems, thereby generating new options to meet the other actors' evolving needs.[11]

Innovations that plug the structural holes exhibit technology and knowledge brokering. Thomas Edison's innovation factory became famous for products that blended existing but previously unconnected ideas and technologies and brokered this knowledge from one industry to another.[12] For this purpose, Edison's factory constructed a network rich in structural holes that afforded speedy access to diverse information sources. However, the benefits of structural holes depend on the context.[13] Having more structural holes in a network is not necessarily better, despite the breadth of ideas that those holes might generate.

Networks with many structural holes can lead to situations where each party pursues its own individual goals. In other words, a high number of structural holes in a network promotes actions and strategies that uphold rivalry and segregation between the parties.[14] Therefore, plugging structural holes creates a denser network, which leads to a more cohesive group of interconnected partners through increased trust, improved collaboration routines, and reduced opportunism. Because of these advantages, new technologies that help close structural holes are especially important in facilitating circular ecosystems.

Mathews and Tan[15] emphasize the importance of the identification and analysis of many "eco-industrial initiatives" that reduce the energy and resource intensity of industrial activities. Traditionally, industrial actors have pursued harmony between the industrial economy and the environment by using resources more efficiently, and by converting wastes from one process into inputs to another industrial process to increase productivity. Information about materials and the intelligence of goods contribute to creating and maintaining the balance between the organization and the environment.

Material Intelligence Enables Industry-Wide Business Ecosystems

Jeff Curie, CEO of Bitvore, a new business intelligence venture, defines "material information" as information that matters to the users and producers of a product.[16] In short, it is information that has a "material" impact. Of course, "intelligence" is about insight, information, and data. Thus, material intelligence provides customers with personal and contextual information about the materials they use to meet their business needs.[17]

Case 1: The Steel Industry. Pearlite (a pseudonym) is a globally operating steel industry giant that specializes in processing raw material to produce steel. The company has a strong focus on discovering how to make its products more intelligent. It is investigating the idea of "steel as a message carrier." Pearlite's vision of material intelligence is to assign highly detailed properties to their products in order to automatize and optimize its customers' processes. In light of this vision, one Pearlite director emphasized how its customers seek materials for "higher-quality products, less wastage, and more accurate audit trails." In turn, this comprehensive audit trail accumulates information to guide Pearlite's future product development.

Material intelligence and the audit trail it enables have tremendous value potential in the steel industry. Giving the material a digital identity enables a new world of potential innovations. In addition to the considerable benefits at the recycling phase, the digital audit trail provides a way of observing the full life cycle of the material. Our findings from Pearlite show that new types of industry platforms have considerable potential in facilitating product-related information flows to align the needs and requirements of different actors, given that "more direct collaboration will help us develop products that bring value to our customers," according to the service director at Pearlite. Similar observations across industry actors indicate a paradigm shift from a strict supplier-customer relationship toward a more collaborative approach involving product-related data sharing in the industry. Different actors that have access to the audit trail can provide innovations that can alter the way that the product moves through the loop and what kinds of material reuse systems become possible. The audit trail would enable material reuse systems, as suggested by Ness and colleagues,[18] without the need for add-on sensors or monitoring devices.

Based on our interviews with managers at Pearlite (see Appendix B), the company executives perceive the virtual characteristics of goods as opportunities to enable the formation of platforms that combine the physical and information aspects of products with service-based value creation. Such platforms involve an important interorganizational structure that facilitates information flows among actors and processes, thus plugging the structural holes in the networks. Shared information helps to optimize and automate the supply chain processes, and to identify new uses for the accumulated data. Executives at Pearlite see that the unanticipated connections and uses of data have the potential to surpass the role of any preplanned information exchange. Therefore, their vision of material intelligence relies on considerable openness.

Digital Platforms Foster Collaboration in Closed-Loop Ecosystems

Most literature on digital platforms focuses on the disruptive potential of technology.[19] For traditional businesses and industries to move toward platform-enabled value creation and capture, they must look beyond the hype about disruptive technology and realize that sensors, telematics, machine-to-machine (M2M), and other technologies are just the nuts and bolts. What really counts is the intelligence that will hold these important technologies together using the infrastructure—the services, the apps, and the technical boundary resources and objects—and with this business model disruption come new ways to create value and innovations.[20]

Case 2: Waste Management. Rubicon Global, founded in 2008, set out to change the waste management and recycling industry. Traditionally, waste management companies have made money by collecting trash. Some companies do attempt to recycle waste, but there is little incentive to do so.[21] Potential revenues from costly recycling are shrinking due to plummeting oil prices, which means more waste in landfills. Rubicon has flipped the industry's revenue model and the incentives for recycling while striving to be entirely green: the aim is to reduce the amount of waste going to landfills and cut down unnecessary pickups while making profit.[22] Rubicon's model is "less waste, more money," making its approach to garbage management the polar opposite of that of traditional waste management companies. How is this possible?

Rubicon does not own any landfills or garbage trucks. It is a facilitator or marketplace between companies wanting to cut their waste costs and local haulers who can bid on jobs. Rubicon also controls the system in a way that avoids unnecessary pickups. Then, Rubicon analyzes the waste and sells off what it can. The revenue comes from two sources: first, whenever a company manages to make savings, Rubicon takes a slice; and second, whatever Rubicon can sell for recycling does not end up in landfills and makes more money for Rubicon.

A software platform controls everything in this new model. Essentially, Rubicon is a technology startup that is attempting to renew a mature industry. Information is key in Rubicon's service operations: they use it to optimize everything. Rubicon is still a small player in the field, but it will be quite exciting to see how such initiatives can transform the waste collection and disposal industry. So far, it has been fascinating to see how Rubicon has aligned its client's corporate interests, Rubicon's own interests, and the broader environmental interests. However, much still remains unexplored. Rubicon's cofounder Morris Moore said[23] that fully exploiting the data collected from companies could be the most valuable part of the whole setup.

Intelligent Nodes Enable the Harnessing of Distributed Networks for Value Creation

Approximately 98% of the world's processors are not in personal computers but embedded into diverse cyber-physical systems[24] that combine virtual and physical worlds. These systems enable new types of closed-loop ecosystems that make use of distributed ledger technologies, such as blockchain technology popularized by the Bitcoin cryptocurrency. Distributed ledger technologies make a great example of systems that bear the characteristics of commonly owned information in peer-to-peer (P2P) networks. Distributed ledger technologies are methods by which parties previously known and unknown to one another can jointly generate, maintain, and share practically any database on a fully distributed basis. Each party receives a copy of the ledger (or part of it) and may then make changes to the database subject to collectively accepted contractual and business rules.

Case 3: Automotive Batteries. The popularity of electric cars has suffered from the long recharging time relative to the distance they are able to travel on a single charge. Stringham, Miller, and Clark suggest that a network of actors can rectify this shortcoming by introducing a systemic change to the value system.[25] In 2013, Tesla introduced a service concept for electric cars, replacing the rechargeable battery pack with a fully charged battery at a service station.[26] If the market adopts such a full swap solution, and the batteries include adaptable microcircuits and necessary technical boundary objects and resources, the intelligent battery concept could benefit from using the distributed ledger technologies.[27]

The intelligence of goods enables new types of transactions in business ecosystems. When a customer leaves the battery at a service station for recharging, the battery connects to a P2P network autonomously created by the smart components involved. Next, the battery starts gathering information on, for instance, the supply and demand of electricity, battery stock levels at the nearest recharging stations, amount of road traffic, and the status of each battery within the current operating range. Having collected all this information, the battery then performs a trend analysis: whether it would make economic sense to buy electricity at the local station and recharge itself right away or to sell the power it still retains to some other party and wait for the market price of electricity to fall.

The node is also capable of performing business intelligence. To carry out trend analysis, the battery may, if necessary, buy additional computing power or any other resources from other goods (such as batteries waiting to be recharged, the drinks vending machine at the station, or a robot vacuum cleaner) that are not using their built-in processors for other tasks at the moment. The battery will look up the supplier offering computing power at the lowest rate in the exchange jointly created by the smart components with the help of the distributed ledger technology enhanced with technical boundary resources and objects. The battery pays compensation for the computing power from its device-specific account to the accounts of the other devices by using, for instance, cryptocurrency.

Once fully recharged, the battery will reconnect to the marketplace generated by the components and start marketing itself to other vehicles in the vicinity that have compatible but low batteries. Moreover, the battery can offer itself to vehicles whose batteries were charged at a higher cost. If the driver accepts the offer and leaves the more expensive battery at the station, the difference between the battery and the vehicle is settled in cryptocurrency, and the vehicle will continue its journey with cheaper electricity. The battery may offer itself at a loss if there is a risk of being stuck at a remote station with little traffic. Another possibility is that—as long as the components are mutually compatible—the battery can offer itself for use in other assemblies, such as small-scale power plants or households that are a part of smart microgrids or nanogrids.

Once the battery has accumulated enough profits on its device-specific account, it will order servicing for itself and pay for the service from its account in cryptocurrency. If there is any surplus profit after all the operating costs, the battery will credit the difference to the company that owns it. In between the payments, the owners will not need to pay any special attention to the battery because it transacts business fully autonomously as if it were a subsidiary consisting of a single component. As a result, there would be no need for costly centralized cloud services or other background processes designed for millions or even billions of batteries. Instead, each battery would buy the products and services it needs from the most affordable supplier autonomously at a given time.

Intelligent goods can be designed for recyclability. For example, at the end of its service life, a battery puts its recycling out to open tender and pays for it from its earnings, ensuring that the customer or company incurs no expense for disposal. As its final action, the battery will credit any "inheritance" left to the company that owns it. The tasks that the intelligent node was programmed to accomplish form a distributed, autonomous network for a platform-enabled business ecosystem.

The Increasing Intelligence of Goods Raises the Issues of Information Management and Data Ownership

Information intensity inside non-durable, durable, and capital goods, supply chains, and nodes is bound to increase. In many industrial fields, the increased information intensity links with the transformation of industrial firms' strategies toward service-based value creation, because addressing customer needs calls for more complex offerings than ever. In other words, many firms are moving from sellable products to service-based value creation. Moreover, given the growing role of technological platforms for multi-actor collaboration, more actors are sharing information about goods. Along with the growing intelligence of the goods, the role of information management in value creation is increasing.

Along with the increasing intelligence of goods, the importance of access versus ownership of data becomes an increasingly complex and debated issue. Our empirical findings indicate that, in general, the possession of data may become less important, whereas the capability to utilize the available context-specific information may become ever more valuable. Even though an organization may have *de facto* control of data, it can only claim its ownership if it is entitled to do so in the legal sense.[28] For example, facts and statistics collected for reference or analysis can be stored and managed. A traditional view of information management is that the organization possesses the infrastructure, such as goods where the data are stored.[29] The ownership of goods is the default assumption in data management when organizations have not made and executed contractual arrangements or the like. In this case, the owner of the goods usually has a natural ability to prevent others from accessing these data by blocking access to goods. Furthermore, within the freedom of contract, the parties can specify to whom the information belongs, what kinds of access rights there are to these data, and whether these rights are exclusive or parallel.

Nonetheless, many supply chain actors, such as suppliers, manufacturers, distributors, service providers, and financing institutions have their own interests in managing both the information related to goods and consumers in different compilations. These interests can entail barring others from accessing the information through the life cycle of the goods. In addition, a party has ownership-like administration of data when it has the ability to deny other parties the use of these data even when it does not have actual ownership.[30]

Intellectual property rights for intangible assets, such as information, however, enter the stage only when someone uses information for specific purposes, for example, as part of an innovation process. For the future, information produced in service encounters as part of the supply chain activity in digital platforms needs to be considered in the same way.

Distributed Ledgers Represent Important Infrastructure Elements in Closed-Loop Systems

From the perspective of intelligent goods, the reliability and accuracy of information will be increasingly significant. Trust and accountability will shape contract policies between parties given that information flows through different interfaces among the actors. Considering the length of the transmission chains, it must be contractually possible to establish the causality of liability. In distributed ledgers, however, there are no lengthy information-transmission chains; rather, the liabilities are shared between the organizations. In the end, the contract and business rules of distributed ledgers will define the strengths of shared information ownership between parties. Furthermore, solutions are being developed where data encryption enables untrusted parties to store, manage, and share sensitive information without compromising its privacy.[31]

A distributed ledger is a key infrastructure element for a P2P network in which organizations can store, manage, and share information to form one data structure of any good.[32] In a permissioned ledger, one organization possesses the authority to permit or prohibit the participation of other organizations to access and/or to edit these data in the distributed ledger. Conversely, in a permissionless ledger, any party, known or unknown to the other participants, is free to access and edit these data in the ledger, as long as it complies with consensus rules mutually agreed upon by the participants. The participating organizations store, manage, and share information in a joint fashion according to a tamper-resistant set of verifiable contract and business rules, backed up by hash functions and cryptographic algorithms.

How to Leverage Different Closed-Loop Systems for Value Creation

Table 1 introduces three archetypes of closed-loop ecosystems and summarizes their distinctive characteristics. We label these archetypes as "inner circles," "decentralized systems," and "open systems."[33]

Platforms for Collaboration in Closed-Loop Ecosystems

Platforms and distributed ledgers may become essential drivers for closed-loop ecosystems. The structures of collaboration in closed-loop ecosystems range from cross-sectoral partnerships to multicentric industrial systems and platforms that enable marketplaces for transactions across the life cycle of an object. The research is still inconclusive on how platform ecosystems emerge and create benefits. Although there are different classifications for platform types,[34] it is difficult to categorize all platforms.

Different types of platforms have alternating logics for value creation. The steel industry case underlines the potential for cross-sectional partnerships to create innovation leverage[35]: different actors expect collective benefits that may materialize in the seemingly distant future. In the meantime, the companies would develop a collaborative ecosystem by opening their internal platforms to their partners, thereby insulating themselves against outside competitors. The Rubicon case exemplifies how multisided markets can create production leverage—they optimize existing processes, generating value to each participant and reducing waste, all the while allowing Rubicon to take its share of the gained profits through its supply chain platform. Rubicon is constructing a multicentric industrial system designed to allocate resources more efficiently. In the case of automotive batteries, autonomous intelligent nodes enjoy a considerable transaction leverage in the proposed marketplace. The marketplace can simultaneously

TABLE 1. Composition of Closed-Loop Ecosystems: A Synthesis.

Archetypes of Closed-Loop Ecosystems	Inner Circles	Decentralized Systems	Open Systems
Examples	*Steel Industry*	*Waste Management*	*Automotive Batteries*
Platforms for Collaboration			
Ecosystem Structure	Cross-sectoral partnerships	Multicentric industrial systems	Marketplaces
Information Exchange Relationship	Long-standing, relational exchange among business partners	Tightly coupled industrial systems for data sharing, and an extensive system of systems in which new and existing actors learn to utilize these data.	Market-based, transactional exchange. Enables anybody to execute practically any interaction requiring mutual trust electronically without intermediaries.
Platform Type	Internal and supply chain platforms[a] supporting business collaboration	Supply chain platform enabling a multi-actor production system	Industry platform, a new infrastructure for transactions
Management of Information Resources and Objects			
Essential Information	Goods-related information	Data collected to optimize resource efficiency in the system	Situational knowledge
Locus of Intelligence	Associated with, but distinct from goods and material	Some level of intelligence at objects (e.g., transceiver capabilities) supported by external network	Located at the object
Data Ownership and Management of Boundary Resources	Shared data repositories. Access to data maintained collectively with boundary resources.	Controlled by a third-party actor. Shared practices and technology to access and share information.	Distributed, accessible by publicly auditable rules. Programmable interfaces as a key boundary resource.
Innovation for Sustainable Recycling			
Drivers for Change	Product commoditization	Optimizing current processes	Disruptive innovation
Value Creation Logic	Collaborative value creation	Multisided market, stakeholder groups hold their own interests	New dominant design, new actors
Innovation Focus	Evolutionary supply chain innovation	Ecosystem-level ambidexterity[b]	Revolutionary, systemic innovation

[a] A. Gawer, "Bridging Differing Perspectives on Technological Platforms: Toward an Integrative Framework," *Research Policy*, 43, no. 7 (September 2014): 1239-1249.
[b] M. L. Tushman and C. A. O'Reilly, "The Ambidextrous Organizations: Managing Evolutionary and Revolutionary Change," *California Management Review*, 38, no. 4 (Summer 1996): 8-30.

help consumers to find the optimal solution to their needs and help providers to find the best possible market deal.

Platforms create shared value and benefits for the participants through network effects. The indirect and direct network effects of platforms can increase exponentially with the number of actors in the platform, providing potential for innovations and increasing the appeal of the platforms.[36] However, monetizing platforms is difficult because openness is what helps to grow the platform but control is what helps the platform owner to capture profits. Our cases present three different logics to address this duality. Pearlite protects its business against outside competitors by developing long-standing information exchange partnerships within its business network. Because collaboration evolves and improves over time, the existing partnerships are soon preferred to new entrants. The network level of control is high on the outside, but low on the inside. In turn, Rubicon has adopted an integrating role in its network, balancing openness with control. The network grows as its members become receptive to new entrants and actor role changes, but at the same time, they control the information flow, ensuring a share of the profits. Finally, open systems have minimal control but strict policies. The system for automotive batteries is open to new participants that are willing to obey the rules. This openness results in a marketplace in which the automated and fluid exchange of information is commonplace.

Boundary resources that permit organizations to share and use shared information are vital for the creation of collective value in platforms. We conducted a survey of the boundary resources that enable firms to participate and enable participation to their digital platforms and ecosystems (Appendix A). According to the findings, almost half of the firms in the technology industries have an application programming interface (API), including a set of programming instructions and standards for accessing a software application or a multi-actor platform.[37] In addition, about a quarter of the surveyed industrial firms have published a software development kit to enable external developers to make applications to the platform. Moreover, almost 20% of firms have published scripts (i.e., programs or sequences of instructions for external programs) to provide some complementary functionality to a platform.

As platform interfaces become increasingly open, more agents will be attracted to the platform ecosystem. Standardization of boundary resources, a central feature of genuinely distributed systems, will create virtuous cycles that boost the benefits to current participants and increase the appeal for new entrants. Making use of such resources enables actors in the platform to leverage the resources from others, thus increasing the potential for innovation, novel production scheme improvements, and efficient transactions. Hence, boundary resources are key components of a thriving closed-loop ecosystem.

Management of Information Resources and Objects in Closed-Loop Ecosystems

Closed-loop value creation raises the question of managing the intelligence of goods and goods-related information. To date, consumers connected through complex social and functional platforms have driven digital productivity, particularly information sharing. Industrial firms have fallen behind in this development. However, the new constellations for value creation build on activities between supply chain partners and organized data. Firms digitize, collect, organize, and share data and content for them to be part of the new systems that create value through services based on information resources.[38]

Administration of information resources varies in different archetypes of closed-loop ecosystems. In the inner circles built for recycling, the key managerial concerns involve governing the goods-related information to enabling the use of the object in the next phase of its life cycle. In decentralized, multi-actor systems, specialized actors add value to the value chain processes by making new connections among the object-related data and actors that may benefit from that data. In open systems working as marketplaces, the essential information determines the current situation and constraints leading to decisions on whether a node should buy or sell its assets. Sharing and utilizing information resources is the key for service-based value creation in all archetypes of closed-loop ecosystems. Technical boundary resources and objects, but also contract and business rules, become even more important when implementing permissionless distributed ledgers. By providing publicly auditable boundary resources and objects, the ecosystem could benefit from innovation activity for larger indirect and direct network effects.

The locus of goods-related intelligence varies among the types of closed-loop systems. As described in Table 1, the intelligence related to goods may be distinct from the goods and materials. Alternatively, some intelligence may reside in the objects operated by the external network. In the intelligent nodes that form distributed networks, intelligence may be located in the object. Concerning material intelligence in the ecosystem, smart instances can carry messages in the supply chain and enable value creation through service. By knowing the history of the instances, actors can better configure their own operations. Product and service instances possess a globally unique identity. Based on that identity, actors can handle the instances and retrieve information on, for instance, the exact composition of the item, process parameters of previous actors, and processing and sorting instructions, in addition to contextual information such as location.

Innovation for Sustainable Recycling in Closed-Loop Ecosystems

Innovation for closed-loop value creation puts the spotlight on the sustainability of the business models in the ecosystem. Although material recyclability is an important condition for the sustainability and profitability of closed-loop value systems, it is not sufficient for sustainable value creation in the circular economy. The entire ecosystem must be favorable to innovating the participants' business models related to sustainable recycling. This view shifts the focus from recycling material to creating value with goods-related information.

Managing self-reinforcing cycles for recyclability calls for courage to iterate with an ecosystem-level business model. Thomas and colleagues[39] suggest different types of collaboration platforms to exhibit different innovation approaches and architectural leverage in terms of technology architecture, activity architecture, and value architecture. In our synthesis of distinct closed-loop ecosystems—inner circles, decentralized systems, and open systems—the value creation logic builds on collaboration with trusted partners, thereby bridging the structural holes in the multisided market and adopting new dominant designs, respectively. For these purposes, the underlying multi-actor platforms manifest evolutionary innovation of the supply chain, optimization of the multi-actor production system, and revolutionary innovation of the supply chain to revolutionize the entire transaction logic of the ecosystem.

Sustainability innovation takes place at both micro (company) and macro (system) levels. In a broad view, micro-level sustainability innovation by companies should link with the macro-level sustainability innovation and its effects within society.[40] A micro-level innovation can result in systems innovation, which refers to the renewal of the socio-technical system (i.e., a set of networked supply chains, patterns of use and consumption, infrastructures and regulations).[41] In a narrow sense, sustainability innovations are inherently systemic and require ecosystem collaboration, although they consist of enhancements within one organization. Berns and colleagues[42] suggest that companies pursuing sustainability innovation will need to develop the ability to operate on a system-wide basis and collaborate across conventional internal and external boundaries. Yet, business model innovation depends on the structure and characteristics of the closed-loop ecosystem.

Synthesis of Findings: Propositions for Further Research and Management of Closed-Loop Systems

Our cases indicate that productivity increases will follow from work and process improvements and process reorganization rather than from technology innovations per se. For example, in Pearlite, the steel company, the innovation focus will move from information technology (IT) systems to firms, teams, and individuals who redesign their roles and responsibilities in the industry system by choosing the best supporting applications and proposing new ways of organizing value creation in their business networks. Based on our findings from the investigated cases, we establish four propositions concerning the influence of intelligent goods on closed-loop systems.

> **Proposition 1:** Traceability of things by means of documented and recorded identification revolutionizes resource management and material recycling in manufacturing.

Information about the provenance of an object is a key resource for enhanced sustainability. Hence, data management and sharing play crucial roles in closed-loop ecosystems. New supply chain practices call for novel approaches to managing goods-related intelligence. To illustrate, "additive manufacturing" builds on the use of recycled raw materials in the local production of components by means of novel manufacturing technologies such as three-dimensional (3D) printing. Such activity requires ample information to be shared and new types of transactions to be conducted among the actors in the production system.

Similarly, ecosystem-level traceability is in the locus of material intelligence. Our findings indicate that effectiveness in the micro-level management of items across their life cycle phases will accumulate macro-level benefits in the ecosystem-level competition. Consider Pearlite's platform to record and maintain the production history of each steel plate in their production line. By providing each plate with a unique identity, all secondary producers can track the items and retrieve information related to them throughout the life span of the products. This capability can facilitate value creation throughout the ecosystem and revolutionize material management on the ecosystem level.

Another example is "remanufacturing," in which old parts are remade and restored to near-new conditions for new deployments.[43] In addition, new types of ownership of goods make the third example: an increasing number of organizations provide goods as a service and charge the customer per operational hours of the goods. This approach necessitates an extensive knowledge of the goods in their contexts of use. It can lead to sharing of the ownership of the goods throughout the life cycle, among all supply chain participants, based on their value-added contributions.

> **Proposition 2:** The increasing intelligence of goods dilutes the importance of the ownership of things.

In the future, the concept of ownership will have to be redefined. Ownership in closed-loop systems is different from ownership in traditional supply chain constellations. The meaning of ownership has traditionally been broad, encompassing the acceptance of liability and responsibility for product life, accountability for errors, the taking of responsibility for malfunctioning, quality, taking initiative, and making independent decisions about matters delegated to the owner of a resource in a supply chain. In contemporary closed-loop ecosystems, actors are responsible for these issues to the next party and finally to the end customer when selling the product. If ownership over the product stays with the manufacturer until the end of its life cycle, a realistic outcome of such a transformation would be the servitization of all the things. Similarly, it is possible to provide materials as a service.

As the intelligence of goods makes its way to a variety of contexts, products might soon include many components that are intelligent on their own. In an information-intensive context, it is possible to share the ownership of the data or the thing across all participants in the supply chain. Alternately, it is possible to separate the ownership of the product from its data even if each participant chooses to retain the ownership of their data.[44] One of the drivers for sharing product data, as shown in the Pearlite case, is that participants strive to add their own value to the final product and maximize their share of the created value in the ecosystem. Alternative constellations in the product and data ownership affect value creation processes in different ways.

Our cases offer three examples of the potential ownership logics within closed-loop ecosystems. Inner circles, such as the steel industry ecosystem, can function with a traditional transaction-based chain of ownership or with a leasing model where functionality comes as a service. However, in both of these situations, the ecosystem has a collective attitude toward the ownership of information resources. Actors such as Pearlite might have a leading role in initiating the data sharing in the ecosystem, but the value creation relies on collectively shared data that are accessible to all the participants. Conversely, decentralized systems manifest logics where a central operator brokers the information flow and facilitates the value creation over its multi-sided market. In waste management, Rubicon collects items discarded by their previous owners, thereby gaining ownership of those items. It may not gain access to historical data, but henceforth controls data management. Last, open systems go the farthest in challenging the inherent assumptions on ownership of goods. With open marketplaces, we may see constellations where "things" equipped with intelligence and smart contracts become self-sustaining entities. Such things participate in open markets, form contracts when they see fit, and make decisions that affect value creation.

> **Proposition 3:** Smart contracts that enable algorithmic transactions between objects become crucial boundary resources for actors in closed-loop ecosystems.

Boundary resources are the opposite of entry barriers. They lower the traditionally high costs of development and commercialization that are usually associated with bringing innovations to the market. Digital platform providers benefit from providing third parties with access to their boundary resources through split revenue models. By under- and overcharging different market sides according to their willingness to participate in the platform ecosystem, platform providers can foster network effects and maximize profits. Providing the market with openly accessible boundary resources is a difficult decision for companies that do not own their manufactured products in the contemporary supply chains. Moreover, this approach can be problematic in terms of closed-loop ecosystems, because relinquishing ownership most often also translates into forfeiting control over the product.

However, well-functioning boundary resources enhance value creation in ecosystems. Consider Pearlite and material intelligence in the steel industry: an insurance company may provide a less-expensive coverage to a product manufactured using better raw material if it knows where the material originated. Ultimately, the end user will yield a better recycling compensation for items with a known composition. Knowing the exact composition of the scrapped materials eases the forming of ideal composition in each batch, thus making the process more affordable. In addition, the alloying elements are often very valuable on their own. In some cases, they are even more valuable than the recyclable bulk material.[45] Therefore, the more-efficient recycling process with more-refined material streams would be beneficial in many ways, as it leads to a higher value of the product for each actor in the value chain, including the original producer.

One of the latest developments in distributed ledger technology, "smart contracts," allows for parties distrustful of each other to store and execute shared programming logic in a completely distributed fashion. Such contracts enable actors to maintain a consensus not only over who owns which assets but also on the rules and the agreements on how individual assets should autonomously behave and interact in the future.

Casey Kuhlman, the CEO of Monax Industries, a startup operating in the field of smart contracts, has said that "[s]mart contracts provide the backbone for automating business processes which reach *outside* of the rotating glass doors."[46] Furthermore, in a recent *Forbes* interview, Don Tapscott, a business strategy expert and an author on distributed ledger technology, stated that smart contracts will profoundly reduce contracting costs outside the boundaries of the corporation, in reference to the transaction cost theory by the Nobel Prize-winning economist Ronald Coase.[47]

Through these smart contracts (i.e., self-executing and self-enforcing computer programs stored in a distributed P2P network), actors can commit their assets to certain behaviors in the presence of predetermined triggering events. Smart contracts would enable manufacturers to design and program their products to function as a part of a closed-loop ecosystem from the moment they are built until the last moment of their life cycle.

> **Proposition 4:** Resolving the challenge of digital trust will enhance the productivity of conducting transactions on goods in closed-loop ecosystems.

Over the life cycle of a product, many parties need to use and manage the data related to a product or a service. Because value creation by multiple actors in a platform-based collaboration is becoming commonplace, the question of digital trust is of fundamental importance. Actors must be confident that the parties involved are who they say they are and that they will do what they promise to do. Without trust, the potential for benefiting from closed-loop systems of any kind is quite limited—no matter how interoperable the relevant systems are.

Distributed ledger technologies enable the creation of a new type of digital trust where no individual party needs to be trusted to guarantee database authenticity. Instead, all that is required is trust in the fact that most of the actors are behaving honestly in the network. Policy makers have an important task to enable smart transactions among actors possessing identities verified through distributed ledgers. In this regard, trade legislation should strictly enforce contractual obligations between nodes and intelligent products in the network, whereby the distributed ledger technology can significantly enhance the productivity of closed-loop ecosystems. The emerging closed-loop ecosystems will eventually do so by guaranteeing safe and secure autonomous transactions between products and services from different companies.

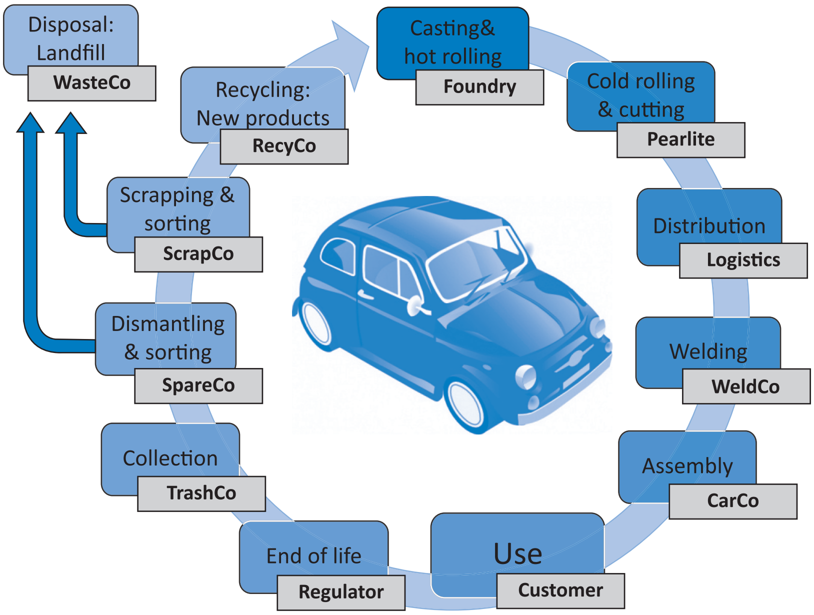
Conclusion

The three archetypes of closed-loop systems employ a distinctive digital platform that merges the physical and digital worlds of material and goods management in the system. Within this fusion, central factors require management if the investments in closed-loop value creation are to generate profit. What remains is harnessing these data to create new value opportunities for the business, thereby rooting the business models in the intelligence of the ecosystem activity at the level of resources. Even though the technology collects and exchanges data between other devices, the company's employees and ecosystem participants need to understand how to use these data before they generate value and become an essential part of a closed-loop ecosystem. Simply improving the resource efficiency of supply chains will not be enough. We need to answer the question, "What really matters?"[48]

Our empirical cases provide managers with insights into the influences of intelligent goods on the structural configurations of closed-loop systems across industries. For example, as the literature has noted, steel products are often reusable after the initial application[49] and, if not, the scrap metal is fully recyclable. In terms of recycling, steel is ideal because it does not suffer from the "down cycling" that is typical of other widely recycled materials, such as plastic or glass.[50] Down cycling means that end products made from recycled material are inferior to those produced from fresh raw materials.

Our steel industry case highlights that, even if the material is ideal for recycling, there needs to be a purpose-built ecosystem working for recycling for the closed-loop economy to prosper. In addition to the long life span of steel, products that originated from a single slab of raw steel might end up in a myriad of different applications. Numerous actors handle these applications and combine them with various items to construct a final product that will be maintained, repaired (using spare parts), and finally discarded. Again, Pearlite offers an example of a plausible life cycle for a steel product that serves as a hood plate in a car (Figure 1). Although the cycle is simplified, it proves that a series of production steps leads to a finished product and that the manufacturing phase involves only a part of the total life cycle. It is possible to produce the vehicle in several ways, but every step in the loop will probably relate to a different actor. In the traditional way of operation, a change in actor most likely will result in a loss of information because the next operator will not be able to track down any of the information generated in previous steps. If they ask the previous actor for details, the information gap will most likely be enormous given that a company cannot be certain where in a batch or production line a single plate delivered to the customer originated.

FIGURE 1. An example of the life cycle of a car hood plate.



For the closed-loop business model to be sustainable in the long run, it needs to be self-reinforcing. This requirement can be met by generating virtuous cycles within the business model. Whereas policy makers may enable future material efficiency by requiring a greater release of data about the use of materials, managers need to accustom their organizations to taking full advantage of material intelligence. For instance, the development of materials for reuse from the outset emphasizes the need to manage the information concerning the material even before the material exists. The use of that information becomes more effective through feedback loops that make use of the domain expertise. Moreover, intelligence pertaining to the composition of a material and the contingencies of its uses makes an important keystone for the recyclability of things. Given the growing importance of information management on technological platforms, the development of a more comprehensive understanding of the promises and perils of information sharing is a fertile area deserving of further study.

In conclusion, when evaluating the potential of a business model in a closed-loop ecosystem, it is important to note that mastering the learning process that leads to new information is more valuable than merely possessing information. Additional empirical and conceptual research is required to develop a more precise and nuanced understanding of closed-loop business models based on multi-actor platforms. In particular, managers need to comprehend the logic of their particular business ecosystem and develop the appropriate capabilities in their corporate networks to compete successfully.

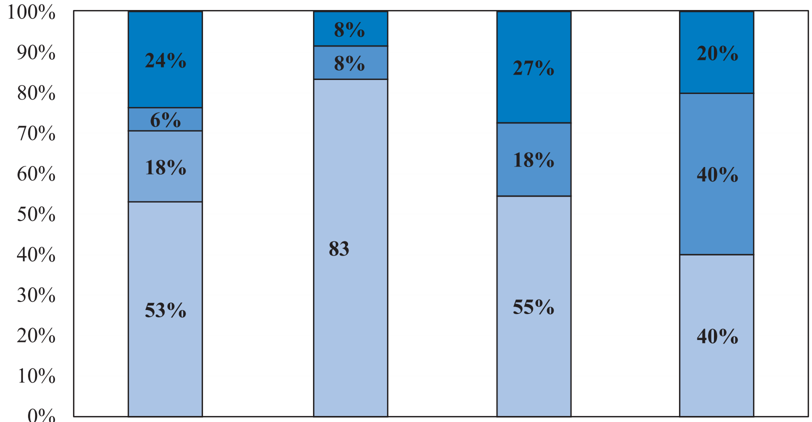
Appendix A

Firms' Technical Boundary Resources for Ecosystem Connectivity

In November-December 2015, we examined firms' capabilities to participate and enable participation to their digital platforms and ecosystems through technological boundary resources. The data cover large- and medium-sized firms in the technology industries, in the service sector, in information and communication technology (ICT), and in other industries.

Data for this analysis are gathered with the Finnish Government project on digital platforms. (For more information, see H. Ailisto, J. Collin, J. Juhanko, M. Mäntylä, S. Ruutu, and T. Seppälä, eds., "Publications of Finnish Government's Analysis," Assessment and Research Activities, No. 19, 2016.)

FIGURE A1. Firms' technical boundary resources for ecosystem connectivity across industries (N = 45).



	Industrial Firms	Service Firms	ICT Firms	Other Firms
API	24%	8%	27%	20%
SDK	0%	0%	0%	0%
Scripts	0%	0%	0%	0%
SDK+API	6%	8%	18%	40%
API+Script	0%	0%	0%	0%
SDK+Script	0%	0%	0%	0%
ALL	18%	0%	0%	0%
DNE	53%	83%	55%	40%

Note: ICT = information and communication technology; API = application programming interface (i.e., any defined inter-program interface provided by the company); SDK = Software Development Kit (i.e., tools for software development provided by the company); Scripts = a program or sequence of instructions that are interpreted or carried out by another program, any complementary functionality; ALL = all of the above; DNE = does not exist (that is, firms in the survey did not offer any of the three resources).

Appendix B

Qualitative Data on Firm-Level Activity in Closed-Loop Ecosystems

TABLE B1. Informants and Interviews.

Company	Interviewee	Date	Duration
Pearlite	Senior executive	March 2014	94 min
	Manager, Products	March 2014	53 min
	Senior executive	March 2014	82 min
	Vice president	March 2014	83 min
	Manager, Applications	March 2014	66 min
	Senior executive	March 2014	66 min
	Senior executive	March 2014	76 min
	Manager, Applications	March 2014	66 min
	Vice president	March 2014	56 min
	Senior executive	March 2014	92 min
	Senior executive	March 2014	65 min
	Manager, Construction	March 2014	40 min
	Manager, Product line	March 2014	73 min
	Senior executive	March 2014	111 min
	Manager, Applications	March 2014	111 min
	Manager, R&D	December 2014	31 min
	Manager, Production	December 2014	151 min
	Head of R&D	January 2015	54 min
	Manager, Services	February 2015	50 min
	Director, Services	February 2015	50 min
Firm A	Software technology manager	April 2014	58 min
Firm B	Accounts manager	April 2014	76 min
Firm C	CEO	September 2014	29 min
Firm D	CEO	September 2014	21 min
Firm E	CEO	September 2014	30 min
Firm F	CEO	September 2014	27 min
Firm G	CEO	October 2014	27 min
Firm H	CEO	October 2014	19 min
Firm I	CEO	November 2014	27 min
Firm J	CEO	November 2014	21 min
Firm K	CTO	January 2015	80 min
Firm L	Manager, Product development	February 2015	37 min
Firm M	Manager, Systems	February 2015	53 min
Firm N	Account manager, Materials	May 2015	95 min
Firm O	Manager, R&D	December 2015	80 min
N = 16	Number of interviews: 35		Total: 35 hr 50 min

Note: CTO = chief technology officer.

TABLE B2. Special Interest Group Workshops Held to Review and Validate Findings.

Topic	Key Questions	Date
Digital platforms enabling advanced services	What is a digital platform? What are the opportunities and challenges?	January 27, 2017
Requirements for provider of digital services	What new capabilities and resources are required for success in digital services?	March 3, 2017
Predictive maintenance service offering	How digitalization is supporting predictive maintenance?	April 19, 2017
Value-based selling, pricing, and business models	How digitalization is supporting value-based businesses?	May 11, 2017
Fleet-enabled services	What are the services that are only possible by fleet-level information?	June 8, 2017
Service offering and portfolio management	How can the service offering and portfolio be developed and managed efficiently?	August 22, 2017

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Notes

1. For more information, see S. Kortmann and F. T. Piller, "Open Business Models and Closed-Loop Value Chains: Redefining the Firm-Consumer Relationship," *California Management Review*, 58/3 (Spring 2016): 88-108. For the scope of this study, the term "closed-loop system" represents a subset of "circular economy," although the terms are often used interchangeably. A thorough analysis reveals some differences in how these concepts are used in the literature. An idealistic vision of a closed-loop ecosystem is what Boulding describes in his essay as the "spaceman economy." It portrays the world as having finite resources, where all new products must be comprised of existing or discarded ones. However, in reality, a more practical approach is what material scientists consider as the desirable goal for the circular economy. Julian Allwood frames such a perspective as, "rather than having circularity as a goal, a more pragmatic vision for a material future would be to aim to meet human needs while minimizing the environmental impact of doing so." We acknowledge the results of the recent literature review by Geissdoerfer, Savaget, Bocken, and Hultink, who define "the circular economy as a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops." These targets may be achieved through the means of long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling. For more details, see, for example, K. E. Boulding, "The Economics of the Coming Spaceship Earth," in *Environmental Quality Issues in a Growing Economy*, ed. H. Jarrett (Baltimore: Johns Hopkins University Press, 1966), pp. 3-14; J. M. Allwood, "Squaring the Circular Economy: The Role of Recycling within a Hierarchy of Material Management Strategies," in *Handbook of Recycling*, ed. E. Worrell and M. A. Reuter (Oxford: Elsevier, 2014), pp. 445-477; M. Geissdoerfer, P. Savaget, N. M. Bocken, and E. J. Hultink, "The Circular Economy—A New Sustainability Paradigm?," *Journal of Cleaner Production*, 143 (2017): 757-768, at p. 765.
2. Following Zott, Amit, and Massa, we define "business model" as a unique arrangement of a firm's value-creating processes and the processes of value capture. In the context of our study, an important aspect of the business model of a firm is the way the processes of value creation and value capture are fitted to the processes of other actors operating in the same closed-loop system. C. Zott, R. Amit, and L. Massa, "The Business Model: Recent Developments and Future Research," *Journal of Management*, 37/4 (July 2011): 1019-1042.
3. In 2015, we studied the drivers and effects of corporate sustainability in almost 100 Canadian companies, the majority of which operated in automotive vehicles manufacturing or electrical equipment, appliances, and components manufacturing. We found that stakeholder pressures and management commitment boost the creation of closed-loop systems in terms of implementing zero waste manufacturing and green supply practices, and that the resulting advancements lead to novel skills, more innovative products, improved financial gains, and environmental benefits.
4. The estimate emerged from our discussions with the Chief Metallurgist and Head of Research and Development at Outotec, Plc, in 2015. The use of copper originated in Asia, but 95% to 97% of all copper was mined in the past 115 years. For more information, see, accessed February 12, 2016, http://www.copper.org/education/history/us-history/.
5. In their recent research report, Seppälä and colleagues (2015) define "digital platforms" as "information technology frameworks upon which different actors—i.e., users, service providers and other stakeholders across organizational boundaries—can carry out value-adding activities in a multi-sided market environment governed by agreed boundary resources and objects. Typically, these actors create, offer and maintain products and services that are complementary to one another. Platforms quintessentially lure and lock in various types of actors with their direct and indirect network effects and economic benefits." For more information, see T. Seppälä et al., "'Platform'—Historiaa, ominaispiirteitä ja määritelmä," The Research Institute of the Finnish Economy (ETLA), ETLA Reports No. 47, November 23, 2015, accessed January 12, 2016, http://pub.etla.fi/ETLA-Raportit-Reports-47.pdf.

6. This perspective is in the heart of the "contingent resource-based theory," which investigates how the value of resources is contingent on the context and the linkages between primary and complementary resources. For more details, see D. Sedera, S. Lokuge, V. Grover, S. Sarker, and S. Sarker, "Innovating with Enterprise Systems and Digital Platforms: A Contingent Resource-Based Theory View," *Information & Management*, 53/3 (April 2016): 366-379.
7. Boulding's famous essay "The Economics of the Coming Spaceship Earth" has been considered as the cornerstone of circular economy discussion. In his essay, Boulding metaphorically describes economy through open and closed systems. He labels open economy, with a limitless supply of expendable resources, as the "cowboy economy" and, in turn, closed economy, without unlimited reservoirs of anything, as the "spaceship economy." Boulding, op. cit.
8. Suren Erkman describes the whole of materials and energy flows through an industrial system as "industrial metabolism." This concept connects closely to industrial ecology literature. Industrial ecology perspective considers industrial metabolism but includes an evolutionary view to unravel the technological trajectories within industrial systems. For more information, see S. Erkman, "Industrial Ecology: An Historical View," *Journal of Cleaner Production*, 5/1-2 (1997): 1-10.
9. Ronald S. Burt introduced structural holes in his book *Structural Holes* (Cambridge, MA: Harvard University Press, 1992). Building on his work, we define a structural hole as a gap between two individuals with complementary resources or information. In turn, a *tertius* is a third party positioned between two or more players, filling the gap between them. In formulating this definition, we acknowledge the work by N. Venkatraman, C.-H. Lee, and B. Iyer, "Interconnect to Win: The Joint Effects of Business Strategy and Network Positions on the Performance of Software Firms," in *Advances in Strategic Management: Network Strategy*, ed. J. Baum and T. Rowley (Bingley: JAI Press, 2008): 391-424.
10. An early twentieth-century sociologist Georg Simmel called such a third party as a *tertius gaudens*, a broker who profits or benefits from competition among two other actors. For more information, see G. Simmel, "The Number of Members as Determining the Sociological Form of the Group. II," *American Journal of Sociology*, 8/2 (September 1902): 158-196.
11. Burt examines this phenomenon through social capital that the structural holes can provide. See R. S. Burt, "Structural Holes and Good Ideas," *The American Journal of Sociology*, 110/2 (September 2004): 349-399.
12. A. Hargadon and R. I. Sutton, "Technology Brokering and Innovation in a Product Development Firm," *Administrative Science Quarterly*, 42/4 (December 1997): 716-749; A. Hargadon and R. I. Sutton, "Building an Innovation Factory," *Harvard Business Review*, 78/3 (May/June 2000): 157-166.
13. G. Ahuja, "Collaboration Networks, Structural Holes, and Innovation: A Longitudinal Study," *Administrative Science Quarterly*, 45/3 (September 2000): 425-455.
14. More accurately, this perspective on structural holes is the *tertius gaudens* variant of brokerage, where the focal actor upholds segregation. For more detailed analysis, see D. Obstfeld, "Social Networks, the Tertius Iungens Orientation, and Involvement in Innovation," *Administrative Science Quarterly*, 50/1 (March 2005): 100-130; D. Obstfeld, S. P. Borgatti, and J. P. Davis, "Brokerage as a Process: Decoupling Third Party Action from Social Network Structure," in *Contemporary Perspectives on Organizational Social Networks, Research in the Sociology of Organizations*, ed. J. A. C. Baum and T.J. Rowley, vol. 40 (Bingley: Emerald Group, 2014), pp. 135-159.
15. J. A. Mathews and H. Tan, "Progress toward a Circular Economy in China," *Journal of Industrial Ecology*, 15/3 (June 2011): 435-457.
16. For more information, see bitvore.com, accessed January 29, 2016, http://bitvore.com/2015/10/what-is-material-intelligence-and-other-faqs-part-ii/#.
17. This definition for material intelligence agrees with prior approaches, which refer to the system-level benefits that accrue from the effective utilization of intelligent goods. For example, see E. Hakanen and R. Rajala, "Material Intelligence as a Driver for Value Creation in IoT-Enabled Business Ecosystems," *Journal of Business & Industrial Marketing*, 33/6 (2018); E. Hakanen, V. Eloranta, P. Töytäri, R. Rajala, and T. Turunen, "Material Intelligence: Cross-Organizational Collaboration Driven by Detailed Material Data" (50th Hawaii International Conference on System Sciences, Waikoloa, HI, January 2017).
18. D. Ness, J. Swift, D. C. Ranasinghe, K. Xing, and V. Soebarto, "Smart Steel: New Paradigms for the Reuse of Steel Enabled by Digital Tracking and Modelling," *Journal of Cleaner Production*, 98/1 (July 2015): 292-303.

19. A. Gawer and M. A. Cusumano, "Industry Platforms and Ecosystem Innovation," *Journal of Product Innovation Management*, 31/3 (May 2014): 417-433.
20. T. Mejtoft, "Internet of Things and Co-creation of Value" (The International Conference on Internet of Things and 4th International Conference on Cyber, Physical and Social Computing, IEE.org., October 2011, pp. 672-677). In the platforms literature: on network effects, see M. Katz and C. Shapiro, "Systems Competition and Network Effects," *Journal of Economic Perspectives*, 8/2 (Spring 1994): 93-115; on multisided markets, see A. Hagui, "Strategic Decisions for Multisided Platforms," *MIT Sloan Management Review*, 55/2 (Winter 2014): 71-80; on complementary assets, see D. J. Teece, "Profiting from Technological Innovation," *Research Policy*, 15/6 (December 1986): 285-305; L. Dahlander and M. Wallin, "A Man on the Inside: Unlocking Communities as Complementary Assets," *Research Policy*, 35/8 (October 2006): 1243-1259; on boundary resources, see A. Ghazawneh and O. Henfridsson, "Balancing Platform Control and External Contribution in Third-Party Development: The Boundary Resources Model," *Information Systems Journal*, 23/2 (March 2013): 173-192.
21. The efficiency of the processes and low cost of energy results in low cost of bulk materials, so that there is little if any economic incentive for recycling waste. Paper is a prime example; there is little motivation for either user or supplier to develop alternative material loops. For more details, see Allwood, op. cit.
22. Following Haigh, Walker, Bacq, and Kickul, Rubicon's approach is a hybrid organization as their business model builds on "the alleviation of a particular social or environmental issue." See N. Haigh, J. Walker, S. Bacq, and J. Kickul, "Hybrid Organizations: Origins, Strategies, Impacts, and Implications," *California Management Review*, 57/3 (Spring 2015): 5-13.
23. For more information about the Rubicon case, see http://www.wired.com/2015/01/rubicon-global/. The business model of the venture is explained at, accessed February 3, 2016, http://rubiconglobal.com.
24. This claim has been put forward in many studies. See, for example, R. A. Santos and A. E. Block, eds., *Embedded Systems and Wireless Technology: Theory and Practical Applications* (Boca Raton: CRC Press, 2012).
25. E. P. Stringham, J. K. Miller, and J. R Clark, "Overcoming Barriers to Entry in an Established Industry," *California Management Review*, 57/4 (Summer 2015): 85-103.
26. Tesla's battery swap concept has some historical predecessors. For example, the Electric Carriage & Wagon Company operated a taxi service with a fleet of electric vehicles, where a central depot for quick battery swaps operated in Manhattan, New York, in 1897. A. Madrigal, *Powering the Dream: The History and Promise of Green Technology* (Cambridge, MA: Da Capo Press, 2011), pp. 75-76.
27. Technical boundary resources and objects reflect how companies ensure the interoperability of different goods such as software development kits (SDK), advanced programming interfaces (APIs), and readymade programming scripts for enhanced functionality of different applications and services (for introduction of technical boundary resources, see Ghazawneh and Henfridsson, op. cit.).
28. For a broader discussion about data ownership issues, see H. Ailisto, M. Mäntylä, T. Seppälä, J. Collin, M. Halén, J. Juhanko, M. Jurvansuu, R. Koivisto, H. Kortelainen, M. Simons, A. Tuominen, and T. Uusitalo, *Finland—The Silicon Valley of Industrial Internet*, Publications of Finnish Government's Analysis, Assessment and Research Activities, No. 10, 2015, pp. 16-17.
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30. L. C. Thurow, "Needed: A New System of Intellectual Property Rights," *Harvard Business Review*, 75/5 (September/October 1997): 94-107.
31. J. Mattila and T. Seppälä, "Blockchains as a Path to a Network of Systems: An Emerging New Trend of the Digital Platforms in Industry and Society," ETLA Reports, No. 45, 2015; G. Zyskind, O. Nathan, and A. Pentland, "Enigma: Decentralized Computation Platform with Guaranteed Privacy," arXiv preprint, 2015, https://arxiv.org/abs/1506.03471.
32. T. R. Eisenmann, "Managing Shared and Proprietary Platforms," *California Management Review*, 50/4 (Summer 2008): 31-53.
33. Richard Scott uses a similar approach to distinguishing among different forms of organizing. For more information, see W. R. Scott and G. F. Davis, *Organizations and Organizing: Rational, Natural and Open Systems Perspectives* (London: Routledge, 2015).

34. These categorizations include works by A. Gawer, "Bridging Differing Perspectives on Technological Platforms: Toward an Integrative Framework," *Research Policy*, 43/7 (September 2014): 1239-1249; Gawer and Cusumano, op. cit.; L. D. Thomas, E. Autio, and D. M. Gann, "Architectural Leverage: Putting Platforms in Context," *The Academy of Management Perspectives*, 28/2 (May 2014): 198-219.
35. In their literature review of platforms, Thomas, Autio, and Gann define leverage as "a process of generating an impact that is disproportionately larger than the input required." They identify three types of architectural leverage in platforms: production, innovation, and transaction logic. One of these logics dominates in a single platform, except in platform ecosystems that equally combine all three logics. For more details, see Thomas et al., op. cit.
36. As stated by Gawer and Cusumano, op. cit., the network effects can be either direct (more users connected to Facebook extends your community) or indirect (more Facebook users equal to more appealing media for advertisers). In both cases, the benefits grow at a drastic pace until reaching a point of saturation.
37. In the blockchain conference (in San Francisco, February 10, 2016), John Wolpert, then Director of Global Products, IBM blockchain, underscores that the distributed ledger technology will soon replace the API economy.
38. T. Seppälä and M. Kenney, *The Tower of Babel Is Being Rebuilt: Business Strategies in Mobile Internet* (Helsinki: Berkeley Roundtable on the International Economy (BRIE)-ETLA Presentation, 2011).
39. Thomas et al., op. cit.
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