1
Introduction

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Society and the economy have changed rapidly and unpredictably over the past several decades, and technology is becoming increasingly reflective of general socioeconomic trends. Basic needs for daily life have been satisfied as technology has advanced, especially until the latter half of the twentieth century.

Historically, technologies have contributed to supporting personal life. On the other hand, as technologies and their applications have advanced rapidly and globally, their contributions to society have not been evaluated adequately.

Technological research and development (R&D) has to be dynamically directed to advance both society and the economy:

- *Society* Environmental issues, such as climate change, earthquakes, and tsunamis, as well as rapid industrial advancement in emerging countries, have impacted society. Conventional technologies and their research activities have not been regarded as appropriate for such changing situations. Therefore, technological R&D must change to achieve sustainability as well as growth.

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- *Economy* There have been several different types of financial crises. The market is globalized, and emerging countries have been advancing their technological skills and accelerating their power in the market. As this global competition has increased, the lifecycle of technology and products has decreased. In particular, earlier component technologies for products and services supplied by leading companies are easily overtaken by later ones, and different companies are dominating the market at different times. In this state of perpetual flux, technology is needed to support the sustainability of both the economy and society.

These fluctuating socioeconomic conditions result in constant reprioritization of human needs. As information can be easily shared through networks such as the Internet, the needs of individuals and societies are rapidly changing and expanding to the global scale to assimilate this information. Although individuals share information, their needs differ. As shared information increases, human needs are diversified and change quickly. Therefore, it is very difficult to predict movements in the market. Market analysis for the majority of users was relatively accurate until the 1960s but gradually became less effective at enabling innovation in technologies and markets [1,2].

In changing society, users' needs also change, which, in turn, further decreases the stability of that society. To accommodate these changing needs, sustainable technological innovation is necessary. Conventional R&D has been effective in managing the direction of R&D [3] and enhancing innovation among organizations by utilizing and sharing their resources outside [4,5]. However, in a changing and unpredictable society, the lifespan of effective technology does not remain as effective in the market as it would with a more stable society [1,2].

The objective of this book is to propose an R&D approach that would create a chain of technologies and markets through an operation that utilizes products and services—that is, an approach that would ensure sustainable R&D results due to successively innovating technological and market processes. Technologies must be flexible and respond quickly and effectively to socioeconomic trends and to changing values for individuals, society, and the economy. Conventional R&D approaches, such as action research, involving collaboration between researchers and developers [6]; problem-oriented development research and experiment-oriented research [7]; and design-based research, through constructing models, methods, and instantiations [8], are defined as processes ranging from technological research to applying the technology to products and services. The R&D process is understood as involving technology transfer from research to development [9–11]. However, these R&D approaches and processes cannot be adapted effectively situations where the needs for products and services are changing or fluctuating [1,2]. The effectiveness of technology developed without considering this factor cannot be guaranteed in real-world conditions [3–5]. R&D must now be oriented toward the bidirectional process of both technology and the market.

R&D must be widely defined as involving the full gamut of concept creation, technological invention, market cultivation, and operation in utilization of products and services [6–8]. In conventional R&D, the processes of concept creation before research and operation in utilization of products and services after development have been inadequate.

All these R&D processes are discussed using real examples, and a new R&D approach, concept-oriented R&D, is proposed as being effective in promoting a sustainable society and economy. Recently systems have been largely dependent on information technology (IT), and concept-oriented R&D is discussed in terms of IT.

1.1 FACTORS OF RESEARCH AND DEVELOPMENT (R&D) APPROACHES

Since society and the economy have been changing, values for individuals and society and their corresponding needs have been varying as well [2,9]. The rate and extent of these changes in values [9] and needs have increased with rapid advances in technology. Technology is developed to achieve goals formulated by individuals [7], by society, or in economic environments. R&D has been adapted to these changing environments.

R&D approaches are dependent on four factors:

- *Needs*—why and for whom R&D is necessary
- *Subject*—what to focus on for R&D
- *Situation*—when to pursue R&D
- *Evaluation*—how to direct R&D

These four factors are characterized by the subfactors listed in Sections 1.1.1–1.1.4.

1.1.1 Needs

The types of products and services vary with the types of users. In the global market, the range of users expands. Segmentation of market users into the following subfactors is advisable for improving R&D:

1. *Majority* When most users require basic products and services for daily life, such as consumer products, they are called the *unspecified majority*.
2. *Minority* Specific users have their own needs, but they are small groups or individuals.
3. *Community* A community consisting of several users, each with individual needs, has a common goal to coexist.

1.1.2 Subjects

Technological R&D subjects are categorized into three subfactors as follows:

1. *Component* A component (or device) has its own specific function in the form of hardware or software.
2. *System* A system is a combination of interacting and interdependent components. The structure of a system is defined as the interactions between the components, and the system has several functions generated from these interactions. A system has its own defined objectives and means of achieving them.
3. *System of Systems* A combination of systems constitutes a system. However, when a system is an integration of systems, each with its own defined objectives, the system is called a *system of systems*. Each system has its originally defined objective and functions. However, as socioeconomic situations change, these heterogeneous systems have to be unexpectedly combined to achieve a newly added objective, while attempting to perform functions for the original objective. In a system of systems, heterogeneous systems are required to coexist in changing situations.

1.1.3 Situations

Research and development is dependent on societal, economic, market, and competitive situations. They are characterized by three subfactors as follows:

1. *Stable* When a situation is stable, long-term R&D can be executed.
2. *Changing* As situations change more rapidly, forecasting and predicting markets and user preferences are give higher priority. Management of R&D is accelerated, and the results are expected to be output within a short time period.
3. *Unpredictable* In changing and unpredictable conditions, the direction of R&D is very difficult to determine. It is important to distinguish between the unchanging and changing aspects in the direction of R&D.

1.1.4 Evaluation

Indices that measure the number of needs fulfilled by technologies being developed and/or produced during R&D can be used to evaluate R&D. These indices must be clarified as technology targets during the beginning, duration, and end of the R&D process [9–11]. The R&D process must be revised if necessary. The indices are categorized into three subfactors as follows:

1. *Specification* Technology can be clearly evaluated by studying its specifications. Superiority of a technology over others is easily compared by analyzing its index.

2. *Performance* A system consisting of several components, each of produced by several technologies, is designed, developed, and operated for meeting life, business, and societal needs. The system can be evaluated in terms of performance as well as technological superiority. A dominant technology is not necessarily optimal for system performance. This system performance index is measured with respect to user needs.
3. *Integrity* Societies consist of several systems, each with its own defined objectives, and must coexist through mutual coordination. When it is difficult to merge their objectives into one, the integrity of these systems has to be achieved when their priorities can be determined or equilibrium is established. Such priorities and equilibria function as integrity indices for heterogeneous systems.

1.2 R&D APPROACHES

As society and the economy change, the four main factors of needs, subject, situation, and evaluation of R&D vary. R&D approaches have emerged for accommodating changes in these factors. These factors are closely related, and their subfactors develop as society and the economy change. From the categorization of these factors and subfactors, three R&D approaches have emerged, as shown in Figure 1.1.

1.2.1 Technology-Oriented R&D

The first generation of technological R&D is *technology-oriented R&D*, meaning that research is motivated to improve and enhance conventional

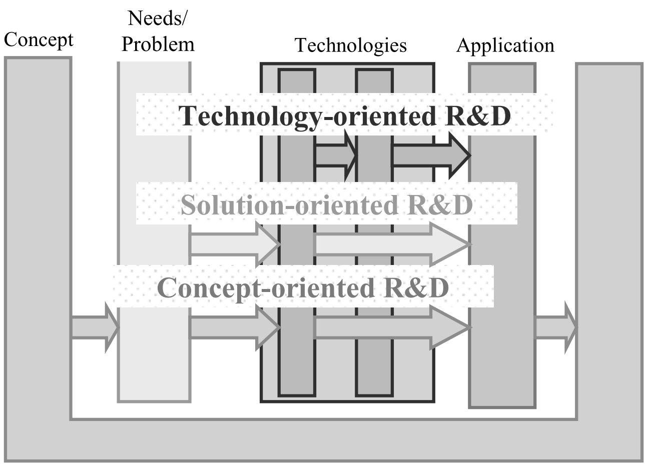

Figure 1.1 *R&D approaches.*

TABLE 1.1 R&D Approaches

Factor	Subfactor	R&D Technology	R&D Solution	R&D Concept
Needs	Majority	•	▲	—
	Minority	—	•	▲
	Community	—	—	•
Subjects	Component	•	▲	—
	System	—	•	▲
	System of systems	—	—	•
Situations	Stable	•	▲	—
	Changing	—	•	▲
	Unpredictable	—	—	•
Evaluation	Specifications	•	▲	—
	Performance	—	•	▲
	Integrity	—	—	•

Notation: •, appropriate; ▲, possible; —, unnecessary.

technologies or to develop new ones on the basis of knowledge of these technologies and science. These technologies are applied to develop previously intended products and services (Table 1.1).

This technology-oriented R&D approach is appropriate under the following conditions:

- Needs of majority users (Section 1.1.1, list subfactor 1)
- Subject of component technology (Section 1.1.2, list subfactor 1)
- Situation of being stable society and market (Section 1.1.3, list subfactor 1)
- Evaluation of technology based on specifications (Section 1.1.4, list subfactor 1)

From the beginning of industrialization until the midtwentieth century, products and services on the market, such as daily commodities, were of insufficient quantity and quality by today's standards but satisfied the common needs of the majority of users at that time (Section 1.1.1, list subfactor 1). Technologies were appropriately applied to create products and services for common needs. Each product or service was used as a component with a specific function for satisfying consumer needs (Section 1.1.2, list subfactor 1). Technological advancement through R&D can contribute to the development of adequate product and service components. Economies in some countries have progress because of technological advancement guided by specific economic development plans under a stable socioeconomic situation (Section 1.1.3, list subfactor 1). In a stable and predictable society and economy, R&D objectives can be clearly planned in detail, with a high probability of success. An R&D plan is needed to clarify the target values as the technology specifications. Evaluation of R&D results is based on the extent to which the target values are achieved (Section 1.1.4, list subfactor 1).

1.2.2 Solution-Oriented R&D

After the common needs of the majority of users have been satisfied in the market, individual users occasionally attempt to satisfy their own personal needs according to conditions or changes in their personal lifestyle or business environment. Individual or minority users might try to resolve problems to satisfy their own specific, customized needs, which may be more complex than, and differ from, the common needs of the majority of users. Hence technology-oriented R&D, which is pursued only to enhance specific technologies, may entail a risk of not being accepted on the market. Second-generation *solution-oriented R&D* is proposed as an alternative to compensate for the possible lack of market acceptance of technology-oriented R&D (Table 1.1).

This secondary solution-oriented R&D approach is appropriate under subfactor 2 listed in Sections 1.1.1–1.1.4 and possibly also under subfactor 1 listed in those sections:

- Needs of minority users (Section 1.1.1, list subfactor 2)
- Subject of system technology (Section 1.1.2, list subfactor 2)
- Situation of changing society and market (Section 1.1.3, list subfactor 2)
- Evaluation of technology based on system performance (Section 1.1.4, list subfactor 2)

Common products and services developed from technology-oriented R&D cannot be satisfied by users with specific needs (Section 1.1.1, list item 2). The solution-oriented R&D process includes problem identification and solution (solution–derivation), technology creation or selection, and product or service development. If necessary, conventional technologies or derivatives there of may have to be applied. These technologies are regarded as solutions to the problem of developing products and services to meet specific needs. As the specific needs of individuals or minority users are not common, they may vary depending on the society and economy (Section 1.1.3, list item 2). A specific problem or need may be too complex to solve or satisfy using only one product or service component, instead, a multicomponent or multifunction product or service can be applied to dynamically adapt to a wide range of situations (Section 1.1.2, list item 2). The integration of components produced using superior technologies does not necessarily generate a superior system. The goal of R&D is not necessarily to create superior technologies in terms of their specifications but to develop a bundle of technologies that are mutually adapted to achieve optimal performance of the system in changing situations (Section 1.1.4, list item 2).

In solution-oriented R&D, needs can be satisfied effectively provided these needs either do not change or change predictably.

1.2.3 Concept-Oriented R&D

Since society and the economy are now complex and globalized, their situations or conditions change quickly and unpredictably. Individual users and organizations can benefit from globalization while confronted with unpredictable disasters. Sometimes, an individual user or organization may create difficulties for others in a global society. In these unpredictably changing situations, it has become increasingly difficult to clarify the existing problems of heterogeneous users and to satisfy their diverse needs. Even if the problems have been identified and resolved, they may change during the R&D process. Therefore, the technologies applied for previously specified problems must be revised. *Concept-oriented R&D* is proposed to compensate for the inadequacies of solution-oriented R&D (Table 1.1).

Concept-oriented R&D begins by researching the background of need trends, problems, and solutions. Then, the fixed or unchangeable portions of the solutions are extracted. This fixed portion of the solution is related to business and technology. For this unchangeable portion, the concept needs to be formulated as a general abstract idea for characterizing a base of business or technology, and its effective coverage and conditions must be restrictively clarified by the primary (major) and secondary (minor) factors as a basis for the R&D approaches. Under the business perspective, the concept of commerce corresponds to the idea of inducing sustainable business activities through products and/or services. The concept of technology drives the generation of new technologies for value-added products and services. These concepts lead to a consistent approach for creating sustainable new businesses and technology.

Along with the utilization of products and services, new needs and problems can be found to cultivate new markets. The concept is regarded as the foundation of the *chain of technologies and markets*.

This concept-oriented R&D approach is appropriate under subfactor 3 in Sections 1.1.1–1.1.4 and may be possibly also under subfactor 2 listed in those sections:

- Needs of community users (Section 1.1.1, list subfactor 3)
- System-of-systems technology (Section 1.1.2, list subfactor 3)
- Situation of unpredictable society and market (Section 1.1.3, list subfactor 3)
- Evaluation of technology based on systems integrity (Section 1.1.4, list subfactor 3)

In these unpredictable and changing situations, users with their own needs try to cooperate with and support each other to achieve sustainability in business, society, and the economy (Section 1.1.1, subfactor 3). It is difficult for heterogeneous systems, each with its own objectives, to tolerate unexpected situations. Users try to integrate their own systems into one system as a community, called a *system of systems*, where they mutually support and cooperate with each other to achieve sustainability with their commonly agreed concept. In this concept-oriented R&D approach, system of systems technologies are derived from the subjects involved in maintaining the community. This R&D process gives rise to the concept of community as a common abstract idea for ensuring sustainability in the community. At the next step in the process, community-based system-of-systems technologies are pursued on the basis of the community concept (Section 1.1.2, subfactor 3). The community is designed to be resilient in function and reconfigurable in structure in changing and unpredictable situations (Section 1.1.3, subfactor 3), while preserving the concept of community. Technologies based on this concept are evaluated in terms of their relative capacity to integrate systems with heterogeneous needs into one system, thus enabling these heterogeneous systems to coexist in the community sustainably (Section 1.1.4, subfactor 3).

1.2.4 R&D Strategies

The technology-oriented R&D approach focuses on a specific target for developing or enhancing a technology, product, and/or service. The solution-oriented R&D approach clarifies the problem of meeting user needs of technology, product, and service as its solution. When socioeconomic conditions change slowly (gradually), with only slight change in the technology targets, and user needs in the market, then the R&D does not need to be refocused or reoriented and the R&D activities of enhancing the technology, products, and services can continue until the results are generated. Technology-oriented and solution-oriented R&D approaches are appropriate for slowly changing and more predictable situations or conditions.

However, when situations change rapidly, the focus on technology and the market in terms of R&D must be reset. Otherwise it is necessary to reduce the R&D timescale by developing technologies through patent licensing from other companies or mergers and acquisitions (M&A). This R&D strategy, called *pile model of R&D*, is employed occasionally for dealing with a competitive market in a fashion, as timely shown in Figure 1.2. However, as situations change, such technologies quickly lose their competitive edge and effectiveness and must be replaced with other technologies. This pile model is not conducive to R&D consistency or to frequent technological innovation [3]. In this model, the technology-oriented R&D approach has one layer with a specific technology and market target. The service-oriented R&D approach is multilayersed since technologies and the market are sequentially added in accordance with the change in users' needs and markets. The technology-oriented R&D approach can be managed as long-term research under stable socioeconomic situations. When the socioeconomic change is gradual, the R&D must be managed on a short-term basis; therefore, the solution-oriented approach is more effective.

On the other hand, in the concept-oriented R&D approach, the concept is created first. R&D for new technologies is then performed consistently on

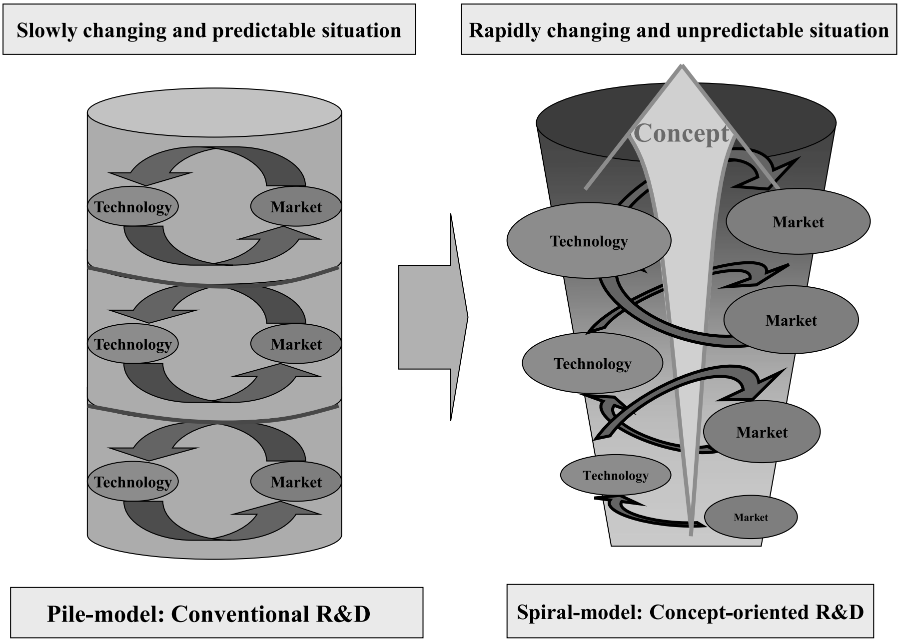

Figure 1.2 *Strategies for R&D.*

the basis of this concept. Utilization of the products and services that apply the technologies results in discovery of new needs. In these processes, new technologies and markets can be evolved. As a result, a *chain of technologies and markets* can be created consistently with one concept. This R&D strategy is called the *spiral model of R&D*, as shown in Figure 1.2.

This R&D approach does not begin with the prediction of a series of technologies and markets; however, along with operation and utilization of products and services, markets are successively cultivated and technologies evolve on the basis of the concept. Therefore, R&D applied using the concept-oriented approach is classified as R&D that is neither long- nor short-term and neither basic nor applied. The R&D strategy has grown from technology-oriented R&D under stable socioeconomic conditions to solution-oriented R&D under changing situations for enhancing technology, products, and services. In unpredictable changing situations, the concept-oriented R&D approach is now being adapted for evolving society and the economy (Figure 1.3). The concept-oriented R&D approach is understood as being *sustainable R&D*.

These three R&D approaches have changed along with the changing socioeconomic conditions. They are characterized by the four factors of needs, subject, situation, and evaluation, discussed in Section 1.1. Since each factor includes three subfactors, there are more than three combinations of subfactors in each factor; there may be other R&D approaches with different combinations of subfactors. The concept-oriented R&D approach is relatively new

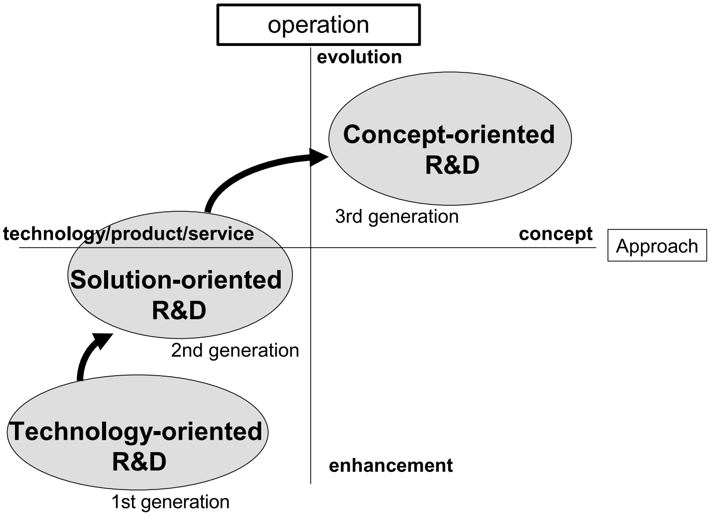

Figure 1.3 *Concept-oriented R&D strategy.*

and it has been applied increasingly under the rapidly and unpredictably changing socioeconomic conditions of the twenty-first century. One example of a concept-oriented approach driving the chain of technologies and markets is discussed in the next section.

1.3 AUTONOMOUS DECENTRALIZED SYSTEM (ADS) CONCEPT AND ITS R&D

The ADS concept was proposed in 1977 [12]. Since then, ADS R&D has been applied consistently for creating innovative technologies [12–16] and cultivating new markets. As a result, a chain of technologies and markets [16–23] is consistently generated according to this concept.

The ADS concept-oriented technologies and innovative applications have been extended to the fields of information systems as well as control systems. For example, The Japanese Shinkansen bullet trains (high-speed railway) control system, the autonomous decentralized transport operation control system (ATOS) for the Tokyo metropolitan railway system [19], the steel production process control system for the Kawasaki Steel Corporation [17], the manufacturing system of Bridgestone Corporation [18], the superurban intelligent card (SUICA) IC-card system for not only fare collection by Japan Railway East and private railways but also for e-commerce [20], and many other industrial automation systems, which are among the largest industrial facilities in the world, were constructed using ADS architecture and technologies. In these applications, ADS improved lifecycle cost, efficiency, software productivity, resilience, and sustainability. The sales volume due to

ADS has surged to US $5 billion, and over 350 patents have been registered internationally.

ADS technologies have been accepted as the de facto standard in consortia such as the Open Device-Net Vendors Association (ODVA), the Object Management Group (OMG), and the Japanese Building Automation Systems Association (BAS).

This concept and the resulting technologies and applications have been discussed at the International Symposium on Autonomous Decentralized Systems (ISADS) founded in 1993, sponsored by the Institute of Electrical and Electronics Engineers (IEEE) and the three Japanese societies of (1) Institute of Electronic, Information and Communication Engineers Society, Japan (IEICE); (2) Information Processing Society, Japan (IPSJ); and (3) Society of Instrument and Control Engineers, Japan (SICE). Several international workshops on ADS have been founded in Asia.

The Internet was developed in the late 1980s and its architecture is the same as that of ADS, which has no master switch for controlling and coordinating the network nodes. In 2001, IBM proposed the *autonomic computing system* as a paradigm that is quite similar to ADS. ADS is now being discussed worldwide, and its concept and technologies have been generalized in various technology fields.

A developmental history of the technologies and real applications based on this concept and their openness and standardization are shown in 5-year increments between 1977 and 2012 in Figure 1.4. Clearly, the chain of technologies and markets in ADS R&D was achieved.

1.3.1 Background and Requirements

As the cost of computing and communication resources have been gradually decreasing, these resources have been widely applied, and their roles in society and business have become more important. Moreover, according to the continuous growth of practical applications and large-scale networking of systems, systems have expanded and become increasingly complex. In large and complex systems, such as railway, factory automation, steel plant production, financial/stock markets, and wide-area information communication, operation must be continuous at all times. Therefore, replacing all components of a entire system simultaneously is not permitted. Instead, stepwise or piecewise construction or replacement of system components, without total operation shut down, is required; this property is termed *online expandability*. If part of the system fails and needs to be repaired or replaced, operation must continue uninterrupted; these properties are called *fault tolerance* and *online maintenance*. Fewer restrictions on computing and communication resources results in more requirements for *online property* of online expansion, fault tolerance, and online maintenance (Figure 1.5).

Conventional computing technologies have been developed under a centralized system concept. Even hierarchical and functionally distributed systems

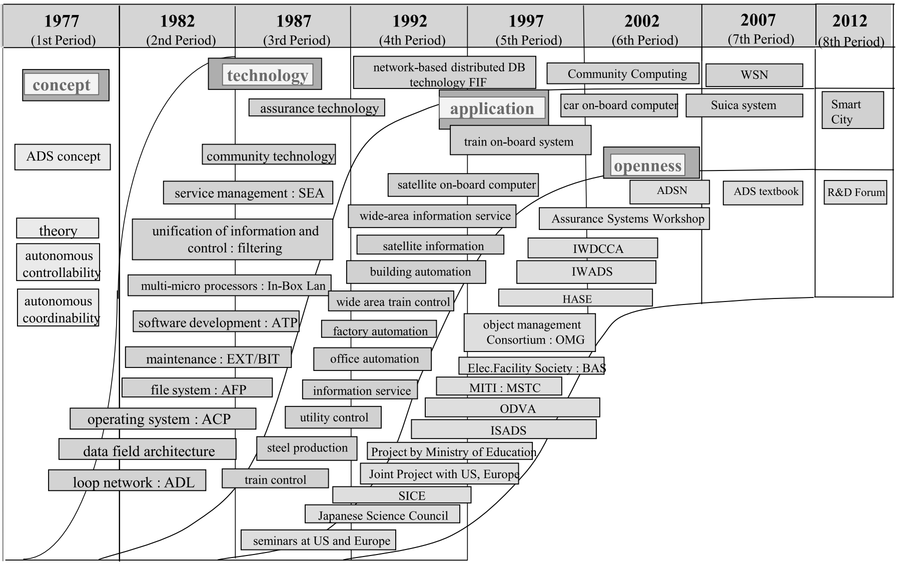

Figure 1.4 *Timeline of R&D on autonomous decentralized system (ADS) and its chain of technologies and markets.*

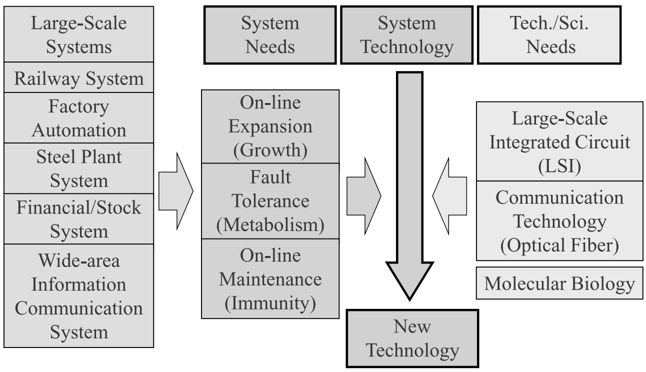

Figure 1.5 *Background and needs.*

are based on the centralized system concept with the requirement that the total system structure and functions be determined in advance. This requirement cannot hold consistently in a system whose structure and functions change continuously.

To achieve the abovementioned online property in a changing system, the ADS concept and its architecture was proposed in 1977 on the basis of a biological analogy. Since then, the ADS concept has been applied to various technologies fields such as communications, multicomputers, networks, software, control, and robotics. ADS architecture and technologies have also been developed and applied in many fields such as factory automation, transportation, information systems, telecommunications, and e-commerce. Since 1977, market and user needs have changed and diversified. At the same time, ADS technologies have also advanced according to these evolving situations.

1.3.2 Biological Analogy and Concept

1.3.2.1 Biological Analogy Organisms operate effectively by virtue of their biological functions. The two basic components of biological systems are cells and organs (Figure 1.6).

In an organism, each cell has intrinsic information called *deoxyribonucleic acid* (DNA), which is uniform in structure. The fundamental functions of a cell, such as metabolism, growth, and immunity, are attained using the local information surrounding it on the basis of DNA. No dominant cell exists, and the cells are equally functioning without master-slave relationship. These characteristics of uniformity, locality, and equality enable organisms to survive. The functions of metabolism, growth, and immunity are related to the online property of fault tolerance, online expansion, and online maintenance of a system.

Analogously, a biological organ consists of multiple cells that are structurally and functionally homogeneous and have the same DNA. The cells function in unison, with no individual cells dominating within the cellular surroundings or tissue. When an organ cannot adapt to the rapidly and widely changing environment internally or externally, homeostasis for stabilizing the multior-

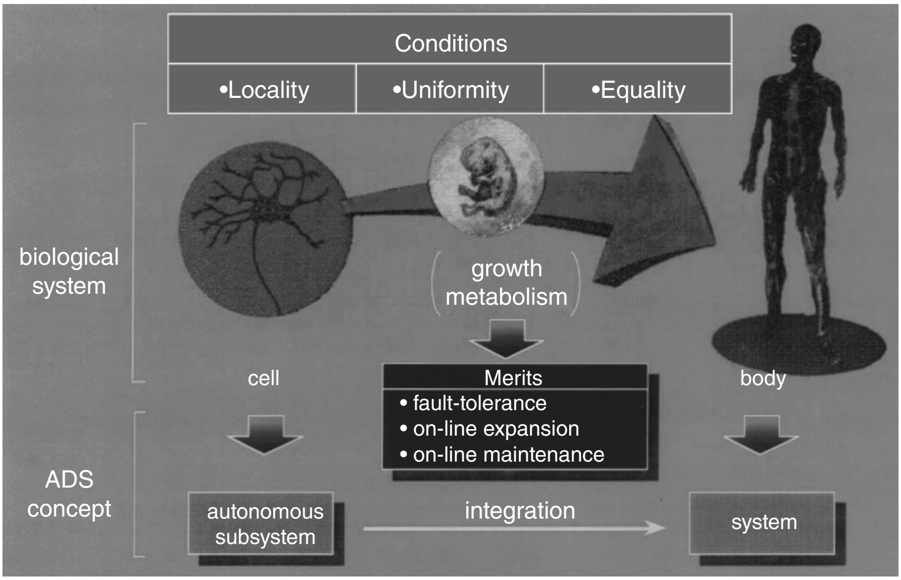

Figure 1.6 *Biological analogy.*

gan biological system is achieved by this homogeneous activity among the cells, thus ensuring the autonomy of the cells and overall functionality of the system.

The totality of an organ's structure and objectives cannot be defined. In the growth process, an organ is gradually formed by the integration of homogeneous cells. The cells perform their heterogeneous functions by linking with other organs to adapt to the environment homogeneously, ensuring the agility of the system. When a cell malfunctions or cannot function effectively, another cell assumes its functions; in other words, the functions in a living system are interdependent yet mobile. Cells in communicate and function autonomously to achieve metabolism, growth, and immunity, which are similar to the online property of fault tolerance, online, expansion, and system maintenance.

1.3.2.2 Concept Opportunities and challenges for creating highly complex, efficient, and dependable business and control systems have been steadily increasing. They are driven by continuous growth in the power, intelligence, adaptability, and openness of technologies applied in computing, communication, and control systems. Dynamic changes in socioeconomic situations demand that next-generation systems be based on adaptive and reusable technologies and applications. Such systems are expected to exhibit the characteristics of living systems composed of largely autonomous and decentralized components; these are ADSs. As shown in Figure 1.7, such a system is characterized as follows:

1. In the system, being faulty is normal (nonnormal is normal). Some of the subsystems may be faulty and need to undergo repair and construction; that is, normalcy in a system is in fact *nonnormal* meaning that the system is almost constantly morphing and expanding, without interruption.

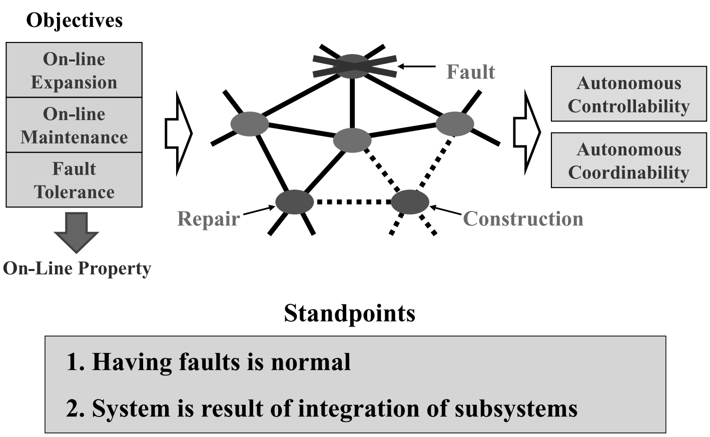

Figure 1.7 *Concept of autonomous decentralized system (ADS).*

2. The system is the result of the integration of subsystems. A system consists in the integration of components, sometimes termed *subsystems*. The objectives, structure, and functions of each subsystem should be clearly defined, but the entire system cannot be clearly defined in advance.

From these perspectives, a system is classified as ADS if the following two properties are satisfied:

1. *Autonomous Controllability* Even if any subsystem (component) fails, is repaired, and/or is newly added, the other subsystems can remain in operation and continue to function.
2. *Autonomous Coordinability* Even if any subsystem fails, is repaired, and/or is newly added, the other subsystems can intercoordinate their individual objectives and can function in a coordinated fashion.

These last two properties ensure the online property of fault tolerance, online maintenance, and online expansion. They suggest that every "autonomous" subsystem requires intelligence to manage itself without being directed to or from the other subsystems, and to coordinate with the other subsystems.

An ADS is possible with autonomous controllability and autonomous coordinability; therefore, each subsystem is required to satisfy the following three conditions (Figure 1.6):

1. *Uniformity (in Structure)* Each subsystem is uniform in structure and is self-contained; therefore, it manages itself and coordinates with other subsystems.
2. *Locality (in Information)* Each subsystem manages itself and coordinates with other system only on the basis of local information.
3. *Equality (in Function)* All subsystems are equal in function; no master–slave relationship exists.

These three conditions represent a complete departure from the *centralized system concept*, which specifies that the totality of the system has to be predetermined. The structural composition of the system is multiple heterogeneous subsystems. A specific master or coordinator subsystem needs information on the entire system to manage or coordinate all the other subsystems. The hierarchical system and functional distributed system concepts are based on the same conditions as the centralized system concept: (1) multiformity (in structure), (2) globality (in information), and (3) inequality (in function).

1.3.3 System Architecture

1.3.3.1 Data Field Architecture Construction of an ADS on the basis of *data field* (DF) architecture with no central operator or coordinator is possible.

The DF architecture is composed of two technologies: content code communication for autonomous coordinability and a data-driven mechanism for autonomous controllability. As shown in Figure 1.8, each subsystem has its own management system, consisting of a self-managing *autonomous control processor* (ACP) that functions in coordination with other subsystems. Each subsystem, called an *atom*, consists of application software modules and an ACP. The DF in the atom is called the *atom data field* (ADF).

1.3.3.2 Content Code Communication All subsystems are uniformly connected only through the DF with a uniform interface; all data are broadcast into the DF as messages (Figure 1.8). A message includes an individual datum and its corresponding content code defined uniquely by its content. A subsystem autonomously selects to receive a message on the basis of its content code (this is termed *content code communication*). Each subsystem is not directed to receive the data by the sender specifying the receiver's address. This content code communication enables each subsystem to autonomously send and receive data; that is, no master–slave relationship exists and equality is maintained among the subsystems. In other words, although each subsystem does not need to detect relationships among the sources and destinations, it must specify the content codes necessary for the application modules in the subsystem to process their attached data. This content code communication feature ensures the locality of information, which enables each subsystem to coordinate with the others; thus, autonomous coordinability is achieved.

1.3.3.3 Data-Driven Mechanism Each application software functional module in a subsystem begins to perform after either all necessary data (AND execution) or part of the data (OR execution) are received. This is referred to as a *data-driven mechanism*, which loosely couples modules. Each subsystem

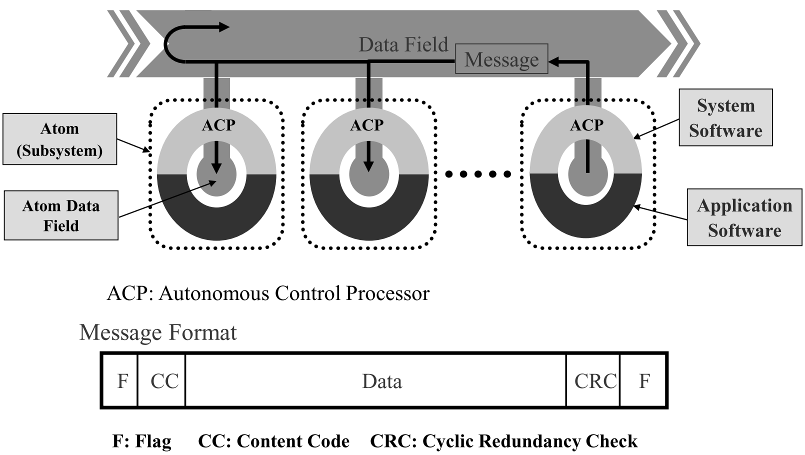

Figure 1.8 Data field architecture.

autonomously determines and controls its own action. Then the modules asynchronously execute. Content codes (CC_1, CC_2, . . .) required for application software functional modules (M_1, M_2, . . .) are preregistered in the executive management system ACP, which can dynamically and autonomously assign necessary content codes in accordance with the specifications or conditions. The subsystem does not need to inform other subsystems as to whether the content codes assigned to the ACP are changed. Every ACP has functions for autonomously managing, checking, and processing and supporting the test and diagnosis. The function of the application software module is characterized by the relationship between the content codes of the input and output data (Figure 1.9). Therefore, autonomous controllability is achieved.

1.3.4 Chain of Technologies and Markets

Chain of technologies and markets on the basis of the ADS concept is discussed using brief examples of R&D based on the ADS concept (Figure 1.10).

1.3.4.1 Global Competition and Cooperation in the Twentieth Century

These two topics are discussed in outline format:

1. *Global Competition*
   a. *Background* Around 1985, global competition among steel production companies had intensified because companies in emerging countries had earned a larger share of the market, due to low costs and relatively high quality. On the other hand, the market had been unpredictably and rapidly expanding because of increased automobile production in advanced and emerging countries. The Kawasaki Steel Corporation (now UFE Holdings, Inc., Japan), which has almost always undergone modifi-

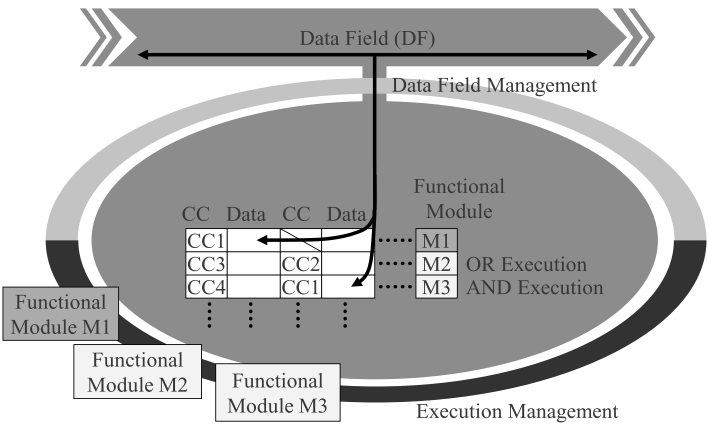

Figure 1.9 *Data-driven mechanism.*

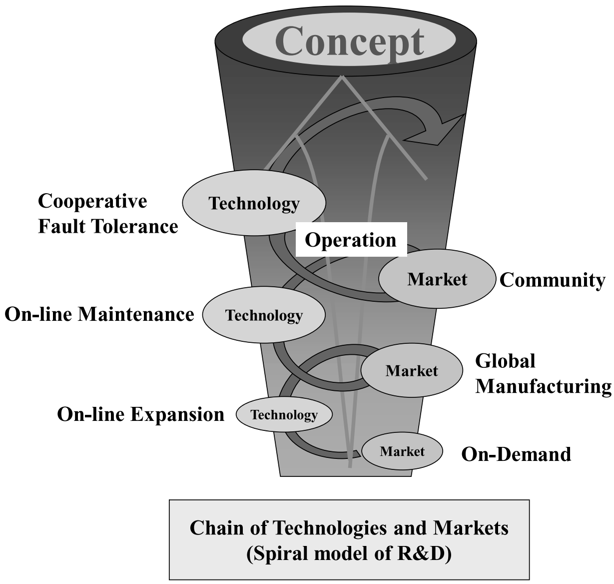

Figure 1.10 *Chain of technologies and markets based on ADS concept.*

cation and expansion to meet the global competition under the unpredictable changing market conditions, is discussed as an example. ADS concept-oriented R&D, in which a nonnormal situation is assumed as normal (i.e., a system is almost always changing and expanding), effectively matches steel production [17].

b. *Market: On-Demand Production* Customers' automotive purchase needs are diverse. However, they usually expect their cars to be delivered within 7–10 days. The automaker uses the just-in-time manufacturing method to avoid the risk of overstocking the cars. Thus, it demands the steel production company to deliver the steel with the required quality and quantity in the specified order; that is, there is *on-demand production* for both the automaker and the steel production company. It is almost impossible for the steel production company to estimate the production volume for various qualities of steel in advance. Moreover, the quality and cost of the steel must be improved daily under intense global competition.

c. *Technology: Online Expansion* Since customers have multiple needs, the estimation error of production for different car purchase orders (POs) increases, along with an increased risk of losing sales or inventory increases. On-demand production is required for decreasing this risk. Previously, automated steel production processes were disconnected while the work-in-process stock between processes was prepared. Moreover, the steel quality must be improved and cost decreased under intense global competition. Meeting the needs of on-demand, high quality, and low cost is possible at two levels to improve the processes on the daily level and to integrate the processes in production on a monthly basis. However, in unpredictably changing situations, which portions of software and hardware in the process are to be improved and which processes are to be integrated and when cannot be predicted. Therefore, each hardware or software module component must be autonomous for revision and modification without interrupting operation of other components. The steel production process must also be autonomous, and each process has to be successively integrated without interrupting systems operation; that is, every component and system must be autonomous. ADS-concept-based online expansion technologies have been developed in multiple levels of hardware, software modules, computers, and systems for modifying, adding, and integrating without interrupting operation. A chain of markets under global competition and technologies for online expansion on the basis of the ADS concept has been created (Figure 1.10).

2. *Global Cooperation*

   a. *Background* In the next step from global competition to global cooperation, many companies have tried to cooperate globally in business activities. For example, they constructed factories and offices worldwide for manufacturing products and providing services. Around 1990, the tire manufacturer Bridgestone Corporation had more than 30 factories worldwide [18]. Their globally distributed factories install the same quality production machines in their lines to guarantee uniform quality and productivity among the factories. All factories operate jointly to adjust production to obtain higher profitability according to logistic expenses and currency exchange rate fluctuation. On-demand production for one factory in global competition was possible, as described for the steel production company in paragraph 1 (above). In this example, however, the new requirement of real-time operation with globally distributed factories has arisen. The successive chain of markets and technologies based on the ADS concept is discussed.

   b. *Market: Global Manufacturing* As tires manufacturing has globalized, one challenge is to guarantee the same quality at all distributed factories. Each factory is constructed and operated with the same facilities and materials. Tire quality depends on the precision work in the chemical process of several hundred materials. The production quantity at each factory has been regulated to the second as the ordered volume to the factory; that is, on-demand production as described in paragraph 1 is applied. Every year, 10% of 20,000 types of tires have to be replaced with new ones to adapt to customer needs and compete with other manufacturers. When a new product is added, the manufacturing methods and processes in all factories worldwide must be rapidly modified and expanded. Through frequent modification and expansion in the system of each factory, the index values, such as the process operational and failure rates, and product-quality, become different among factories. The company must attain the highest index values at each factory. Global cooperation among distributed factories is expected to improve these indices.

c. *Technology: Online Maintenance* In the global market, on-demand production and flexible manufacturing under global competition generally apply to factories worldwide. In globally distributed factories, it is not possible to centrally regulate all their real-time processes

There are three requirements in global manufacturing systems with remote sites in different cultures: (1) each system in all factories should be operated to achieve optimal values in product quality and factory efficiency for on-demand manufacturing—however, there may be discrepanies in these values among different factories; (2) it is necessary to rectify the gap in the levels of skilled labor in globally distributed factories; and (3) maintenance in all factories worldwide should be conducted without interrupting system operation.

In R&D, the online maintenance technology on the basis of the ADS concept has been proposed and applied to satisfy these three requirements. The systems in all factories are connected through a worldwide network. Each system autonomously broadcasts the input/output real-time process data to the network. The systems autonomously select to receive the real-time process data sent from the other factories. The data include the input/output real-time data and their sequences and timing.

When factories are manufacturing the same product, each one can autonomously compare the generated data in the factory with the received data from the other factories to detect discrepancies among them. On comparison of these data of all factories, the factories' systems are adjusted to achieve the highest quality and efficiency. The first requirement of quality and efficiency is met by using ADS-concept-based online maintenance technology.

Moreover, engineers and managers of each factory can recognize any discrepancies in monitored data among the factories and try to improve the system. The second requirement for acquiring skills is satisfied by using the online maintenance technology.

The input/output of real-time data generated from the module in online mode can be used by the modules in test mode, which are repaired or modified but not yet operating in online mode. The test result data generated from the test mode module are also monitored by any other module. They can verify whether the test module is confirmed by comparing the input data of the online mode and the output data of the test mode. Real-time test data generation is important in online maintenance technology, especially under complex and frequent modification without interrupting system operation. The use of real-time data generated from the online mode module as the input data for the module in test mode reduces the heavy burden involved in generating real-time test data, which includes not only the data content but also the timing and sequences of the input/output data. The third requirement for maintenance is also satisfied by online maintenance technology.

A chain of technologies in online maintenance on the basis of the ADS concept and markets with global cooperation has been created (Figure 1.10).

1.3.4.2 Community Service in the Twenty-First Century

Background Around 2000, the global economy became more unstable, but demand in service and sustainability increased. Through global corporate activities, large cities, such as Tokyo, have been rapidly expanding, with increases in population and vehicular traffic. The Tokyo metropolitan railway system is the largest in the world. It covers the entire Tokyo metropolitan area with 20 train lines, 16 million passengers per day, 7300 trains per day, and 318 stations. Train service is 20 h/day, 365 days per year. During nonservice hours, maintenance and tests are conducted. The Japan Railway Company was privatized in the late 1990s. Since then, it has emphasized passenger service as well as safety and punctuality. The global activities have accelerated in the city, where organizations and people are both cooperative and competitive, thus increasing the transport amount and time. Local communities in major international cities, such as Tokyo, have the heterogeneous needs of mission as public transportation and of service for the passengers' lives in the Tokyo metropolitan community. Accommodating and ensuring the compatibility of heterogeneous needs in unpredictably changing situations in a community is discussed, as is the chain of technologies and markets based on the ADS concept [18].

Market: Community A *community* is defined above as a group consisting of several members with their individual needs but with a common goal to coexist. The Japan Railway Company has been operating trains in the community of the Tokyo metropolitan commuter belt. Community members expect much more punctual, safe, frequent, fast, and longer operation from the public transportation system. They also expect operation to continue during reconstruction and enhancement of the system. Even if an accident occurs and trains are delayed, passengers expect not only quick recovery from the delay but also flexible rescheduling of the timetable. They also expect to obtain information on the traffic conditions of all train lines and on alternate routes from the point of the accident. On the other hand, it is necessary for the company to reduce labor costs and reserve time in after-midnight service for maintenance. In the communities within the metropolitan area's commuter railway system, there are heterogeneous needs of passengers who need guaranteed transportation and information. These conflicting needs are related to the physical control of trains and to cybernetic information provision.

A community must be sustainable and resilient for its heterogeneous members to coexist.

Technology: Cooperative Fault Tolerance A community is not global but local. In a community of passengers within the huge Tokyo metropolitan commuter belt area, various members and their needs have been unpredictably changing and are heterogeneous. However, they wish to coexist in the community. The autonomous decentralized transport operation control system (ATOS) in the Tokyo metropolitan commuter belt area has been developed on the basis of the ADS concept since 1997 [19]. This infrastructure is so large that the development term has expanded to more than 10 years since 1997. However, during development, train service cannot be interrupted and the system can be only incrementally expanded without shutting down. Even after the completion of construction, some parts of the system have been successively modified because of changing user needs. The technologies of online expansion in global competition (Section 1.3.4.1, paragraph 1) and online maintenance in global cooperation (Section 1.3.4.1, paragraph 2) can be applied in this example.

In this community, members must coexist with their heterogeneous needs. The problem is not to select some of their needs but to balance them. One major difficulty is the need to develop a physical control system having real-time and highly reliable properties coexisting with a cybernetic information system with high response rate and throughput. Conventionally, these systems have been independently constructed and operated.

The ADS concept is adequately applied for these heterogeneous systems to coexist by autonomously controlling their own responsible functionality and coordinating their functions. One technology based on the ADS concept is *cooperative fault-tolerant technology*. The fault tolerance for the mission-critical system of train transportation is important for guaranteeing safety. On the other hand, the level of fault tolerance for the information system is relatively low, and several bit errors and losses are acceptable because of retransmission of data and reexecution of the module. When both the control and information systems are designed to have the same high levels of fault tolerance, the total system cost is too high. Even in facility control systems, several levels of fault tolerance must be guaranteed. Functionality directly related to safety has to be maximum in fault tolerance, but functionality in other operations, such as nonduty air conditioning, are low. As traffic volume and connecting train lines increase, the level of fault tolerance increases. In other words, multiple levels of fault tolerance have to coexist in one system and the levels vary over time.

In ADS, each computer is connected to the system network, and the data, with its content code revealing the meaning of the data, are broadcast in the data field (DF) among them. Each computer with a unilateral interface to the DF is autonomous in determining whether to receive the data on the basis of their content and to begin execution of the software module when all the data with the necessary content codes are received. Therefore, the module can be installed in any computer in the system and executed asynchronously. The module can be installed in multiple computers according to the required level of fault tolerance. The multiplicity of modules stored in several computers can be varied over time and modified as required without interrupting system operation. Any module can autonomously select to receive the data with the same content code generated from multiple modules through the DF, check for inconsistency among the data, detect faulty modules according to the majority results, and exclude error data. The computer can autonomously determine whether its installed module generating the error data is faulty and correct its own error data.

Cooperative fault-tolerant technology exhibits the degree of fault tolerance not by computer redundancy but by multiplicity of modules. This multiplicity can be flexibly changed without modifying or turning off any computer. Moreover, the computer, including the faulty module, can revise itself and continue operating by using the data generated from the other normal computers. The computer autonomously checks for and revises faults in its own module.

A chain of technologies in flexible fault tolerance or assurance [22] on the basis of the ADS concept and markets of a community with heterogeneous requirements has been created (Figure 1.10).

The three systems discussed in Sections 1.3.4.1 and 1.3.4.2 exemplify the chain of technologies and markets on the basis of the ADS concept and through actual operation. The background of the trend from global competition to global cooperation is common worldwide. Furthermore, there has been a global acceleration in the new trend toward the community for achieving sustainability of human life, company activities, and a clean, safe environment. For example, the smart city and the smart electric power grid are considered parts of communities. In the future, different types of communities will be required and discussed for global sustainability. Therefore, the concept-oriented R&D approach has been a driving force for market cultivation and technological innovation.

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