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# System innovation through stepwise reconfiguration: the case of technological transitions in Dutch greenhouse horticulture (1930–1980)

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Although transitions are usually perceived as technological substitution processes, the article shows that stepwise reconfiguration is more likely for supplier-dominated sectors. In this transition pattern, novelties are initially adopted as ‘modular innovation’ into existing systems and subsequently reconfigure the basic architecture through new combinations of old and new elements. Incumbent actors survive these transitions through interactions with suppliers of knowledge and innovations. Using Pavitt’s innovation typology, we selected a case study from his supplier-dominated category: greenhouse farming. The article makes a techno-economic analysis of the overall transition pattern in Dutch greenhouse horticulture (1930–1980) and a socio-institutional analysis of the knowledge flows and networks. ‘Innovation cascades’ are identified as a particularly important mechanism in reconfiguration transitions.

**Keywords:** technological transition; reconfiguration; knowledge flows; sectoral innovation system; greenhouse horticulture

## 1. Introduction

In the decades following the end of the Second World War, Dutch farmers became horticultural world leaders, particularly in tomatoes and flowers. This economic success is remarkable because temperature, sunlight conditions and length of growing seasons are not optimal in the Netherlands. This success was related to a rapid transition in greenhouse horticulture, which firstly involved a rapid expansion of greenhouse areas (Figure 1). Farmers focused on vegetable crops (especially tomatoes) and fruits (especially grapes) until 1970, when they diversified into flowers.

Secondly, the transition involved substantial changes in technology, social networks and rules/institutions. In the 1950s and 1960s farmers shifted from the ‘Westland greenhouse’ (with

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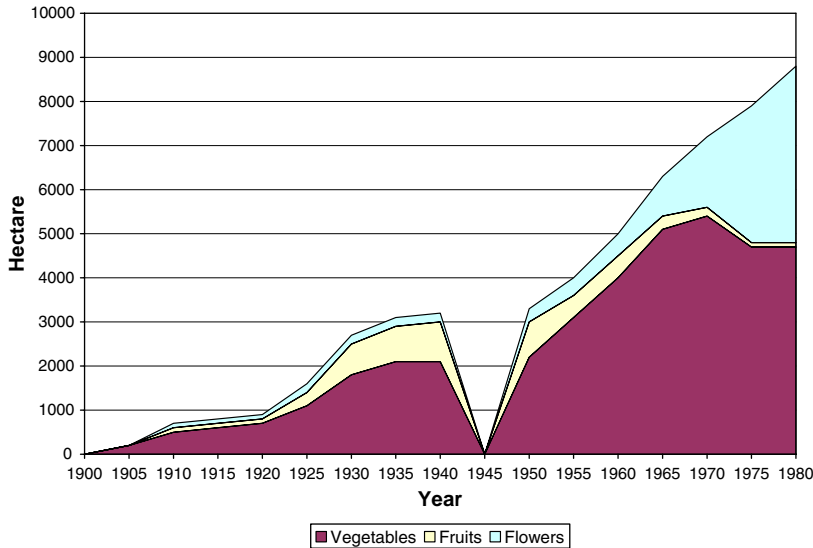


Figure 1. Expansion of greenhouse horticulture per crop category, 1900–1980 (data from Plantenberg 1987).

removable glass plates) to the closed and insulated ‘Venlo greenhouse’. This shift in greenhouse designs was facilitated by the incorporation of many technical component changes, e.g. artificial heat, artificial light, watering, disease control, CO<sub>2</sub> fertilisation and new crop varieties. In terms of networks, the social ties between farmers, universities, technology suppliers and experimental stations became stronger and more differentiated during the transition. In terms of rules and institutions, horticulture changed from craft-based farming dependent on natural conditions (sun, rain) into a vegetable factory, with farmers working as production manager and machine operators. As greenhouse horticulture transformed towards year-round mass production, it became decoupled from the seasonal rhythms that characterised open air horticulture.

The empirical research question is: how did the greenhouse transition come about? The article thus contributes a new case study to the debate around technological transitions and system innovations (Geels 2002; Van de Poel 2003; Elzen, Geels, and Green 2004). The selection of this new case is based on Pavitt’s (1984) innovation typology, which distinguishes five innovation patterns: (1) scale intensive, (2) science-based, (3) government and utilities,<sup>1</sup> (4) supplier-dominated and (5) specialised suppliers.

Most historical case studies in the technological transitions literature come from the first three categories. The transition to turbojets (Geels 2006a) and transitions in psychotropic drugs (Geels, Pieters, and Snelders 2007) occurred in science-based sectors. The transition to automobiles (Geels 2005) belongs to the scale-intensive category. Transition in water management (Van der Brugge, Rotmans, and Loorbach 2005), sewer systems (Geels 2006b) and electricity systems (Verbong and Geels 2007) are from the government and utilities category. The case of greenhouse horticulture has been selected, because it relates to the fourth category (supplier-dominated).

The theoretical significance of this case selection relates to the specific characteristics of supplier-dominated sectors (Pavitt 1984): (1) they consist of many small firms with weak R&D and engineering capabilities, (2) technology and innovations come from suppliers of equipment and materials, government-financed research and extension services, who perform formal R&D

and diffuse the results, (3) competition is cost-based, because many firms operate in a relatively homogeneous market and because users are price sensitive, (4) cost-cutting is an important guiding principle in technological trajectories, (5) these sectors are often characterised as ‘traditional’ or ‘low-tech’ (Von Tunzelmann and Acha 2005); examples are agriculture, house building, traditional sectors of manufacturing, financial and commercial services (Pavitt 1984); (6) these sectors typically involve the interplay of multiple (mundane) components, which form ‘distributed systems’ or ‘configurational technologies’ (Fleck 1994).

We will investigate how these characteristics affected the horticultural transition. Poole and Van de Ven (1989) suggested that developmental processes can be studied from two complementary angles: ‘global analysis’ that captures overall patterns, and ‘local analysis’ that addresses endogenous enactment.

The global (macro, long-run) model depicts the overall course of development of an innovation and its influences, while the local (micro, short-run) model depicts the immediate action processes that create short-run developmental patterns. ... A global model takes as its unit of analysis the overall trajectories, paths, phases, or stages in the development of an innovation, whereas a local model focuses on the micro ideas, decisions, actions or events of particular developmental episodes. (p. 643)

Building on this suggestion, we address two specific research questions: (1) What is the overall transition pattern in supplier-dominated sectors such as greenhouse horticulture? (2) What are specific actor-related mechanisms in these transitions? With regard to the first question, we engage with the existing literature on ‘disruptive innovations’, ‘technological discontinuities’ and ‘breakthroughs’, which assumes that transitions follow a technological substitution pattern. In contrast, we suggest that transitions in supplier-dominated sectors are more likely to follow a reconfiguration pattern, in which systems are gradually transformed as multiple component innovations are adopted. With regard to the second question, we argue that knowledge flows between firms and universities are particularly important in supplier-dominated sectors, which are characterised by a division of innovative labour, with universities and suppliers doing formal R&D and small firms performing hands-on implementation and learning-by-doing. Knowledge flows and network interactions are therefore particularly important in supplier-dominated sectors. We will combine the sectoral system of innovation approach (Malerba 2002) with institutional theory in sociology (Scott 1995) to analyse the specific networks and institutions that influenced the speed of the Dutch greenhouse transition.

Section 2 elaborates these debates. Section 3 and 4 analyse the Dutch greenhouse transition, focusing subsequently on the overall reconfiguration pattern and underlying knowledge flows. The article ends with conclusions in Section 5.

For the case study demarcation, we choose the 1930–1980 period, when major changes occurred in technology, social networks, and rules/institutions, as indicated above. While these changes constitute a shift from one regime to another, and therefore satisfy our interest in transitions, the demarcation is also somewhat problematic. For transitions that follow a reconfiguration pattern we suggest that it is more difficult to identify clear turning points that signal clear ‘start points’ and ‘end points’. The reason is that reconfiguration transitions are more gradual and continuous change processes (see below). This creates complications for the term ‘transition’ which Webster’s dictionary defines as ‘a movement, development, or evolution from one form, stage, or style to another’. Previous studies used the term ‘regime’ to identify the semi-stable states between which shifts occur. For reconfiguration processes, however, it may be more difficult to demarcate such stable regimes. Although the case study uses the year 1980 as cut-off point, the horticultural

regime experienced further changes in subsequent decades, e.g. related to innovations in genetic technologies and co-generation of heat and power. It is therefore problematic to characterise these decades as stable regimes with only incremental innovation. These considerations imply that demarcations of ‘end points’ and ‘start points’ are not set in stone and are open for debate, particularly for reconfiguration transitions. While acknowledging these demarcation problems, we still think that the study of changes in Dutch horticulture between 1930 and 1980 can deliver interesting insights in patterns and mechanisms of substantial regime transformation.

## 2. Reconfiguration pattern and university–industry knowledge flows

### 2.1. Substitution pattern versus reconfiguration pattern

Most approaches in the innovation studies literature conceptualise transitions as technological substitution process, where disruptive innovations (Christensen 1997), breakthroughs (Nayak and Ketteringham 1986), technological discontinuities (Anderson and Tushman 1990), or pervasive technologies lead to ‘waves of creative destruction’ and the downfall of established firms (Schumpeter 1976). These approaches share the following assumptions of transitions: (1) transitions are characterised by one major, radical innovation or discontinuity, (2) this innovation competes with the existing system, leading to a technological substitution pattern of transitions (Figure 2), (3) incumbent actors are replaced by new entrants.

This substitution pattern is likely in systems that are organised around a ‘core’ technology. Examples are the road transport system, which is organised around the car, aviation systems organised around aircraft, visual home entertainment organised around television and video, etc. While these technologies need complementary components to fulfil functionalities, scholars differentiate between ‘core’ technologies and ‘peripheral’ technologies (Henderson and Clark 1990). Transitions in these kinds of systems usually follow a substitution pattern, when a technological discontinuity replaces the core technology.

This substitution pattern is less likely in supplier-dominated sectors, which tend to be ‘distributed systems’ that function through the interplay of multiple technologies. Greenhouse horticulture, for instance, involves technologies for heating, lighting, fertilising, watering, irrigation and drainage, sheltering and pest control. Likewise, retail systems require multiple technologies for transport, packaging, storing, cooling, scanning and payment. Hospitals and medical systems also involve a wide range of technologies for different activities (e.g. diagnosis, operation, treatment, care). In these distributed systems there is no ‘core’ technology that can be substituted by a single breakthrough innovation. Transitions in distributed systems are therefore more likely to follow a stepwise reconfiguration pattern, which deviates from the substitution

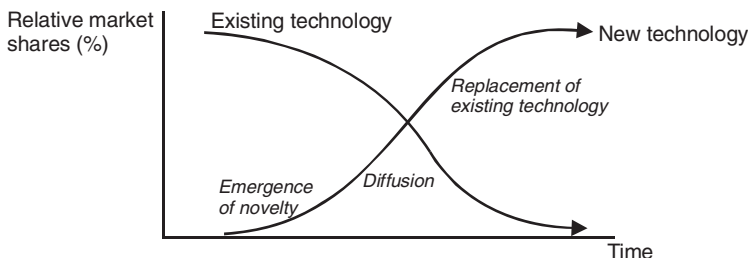


Figure 2. Technological transitions as technological substitution pattern.

pattern in three aspects: (1) they involve multiple (component) innovations, (2) these innovations are incorporated in the existing system as ‘add-ons’ or component replacements; actors may subsequently work out new combinations of ‘old’ and ‘new’ that gradually change the system’s architecture, (3) incumbent actors survive the process and enact the reconfiguration by adopting innovations from suppliers. The transfer of knowledge and innovations to incumbent actors is therefore an important mechanism in reconfiguration transitions. We will elaborate the second point below, using insights from the literature on modular and architectural innovation, and address the third point in the next section, by expanding the sectoral system of innovation approach.

With regard to the second point, innovation in complex technical systems can be directed at components, architectures or a combination of both (Henderson and Clark 1990). Modular innovation means that components are replaced without affecting other components or the system architecture. Architectural innovation means that the components stay the same, but the linkages between them change. Radical innovation involves changes in both components and architecture (Table 1).

Modular innovation is possible when linkages between system components are characterised by loose coupling (Simon 1973). Loose coupling means that components operate dynamically independent of the detail of other components; they are only connected through functional inputs and outputs. In technical systems, loose coupling means that components are organised as independent modules. This permits modular innovation or replacements within one component without requiring synchronous changes in other components (Sanchez and Mahoney 1996). Our emphasis on modular innovation deviates from Fleck’s (1994) views on ‘configurational technology’. He uses this term for his studies of robotics, production systems, computer-aided production management (CAPM) and information technology (IT) applications, where configurations are ‘built up from a range of components’ (p. 637). While this term is useful, we argue that his cases are examples of tightly coupled systems that function only when all components are aligned and tailored to each other.<sup>2</sup> In contrast, loosely coupled systems may still function, although perhaps less efficiently, if problems occur in particular components. For example, crops will still grow in greenhouses if heating or lighting systems break down. So, while innovation in tightly coupled configurational systems involves the development of (and tinkering with) integrated systems, innovation in loosely coupled systems may also involve modular innovation.

The innovation categories from Table 1 do not always remain neatly separated. We suggest that reconfiguration transitions start as ‘modular innovation’ and subsequently turn into ‘architectural’ or ‘radical innovation’, when the new technologies form reasons for adjustments in (linkages between) other components.

To elaborate different phases, we incorporate these ideas into the multi-level perspective (MLP) on transitions (Geels 2002). Although the MLP initially focused on technological substitution processes, with radical niche-innovations struggling against existing regimes in the context of wider landscape developments, new work distinguishes different transition pathways, including reconfiguration (Geels and Schot 2007). We contribute to this new line of work by proposing three

Table 1. A framework of innovations (Henderson and Clark 1990, 12).

	Components reinforced	Components overturned
Architecture unchanged (linkages between components)	Incremental innovation	Modular innovation
Architecture changed	Architectural innovation	Radical innovation

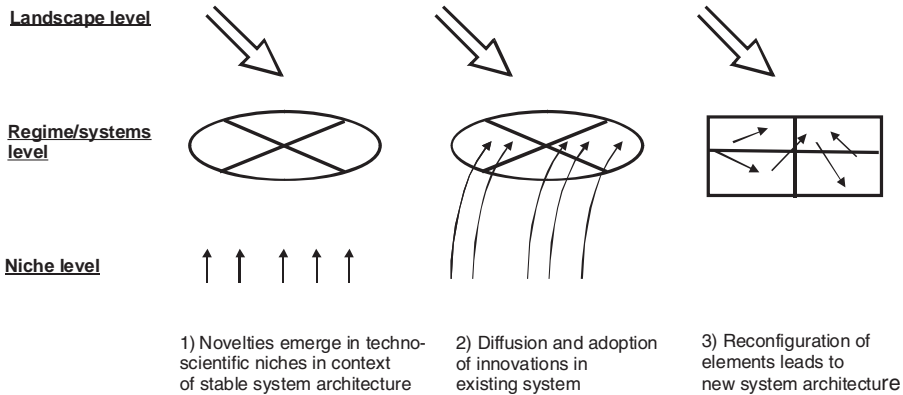


Figure 3. Transitions as reconfiguration pattern.

phases in reconfiguration transitions (see Figure 3): (1) universities or suppliers develop radical novelties (which the MLP conceptualises as niche-innovations), (2) these innovations are adopted into existing systems as ‘modular innovation’, either as symbiotic add-on or as replacement of existing components, (3) new combinations of old and new components lead to changes in the system architecture; because the new combinations and reorganisations allow the new technologies to reach their full potential, major performance improvements typically occur in the third phase.

**2.2. University–industry knowledge flows in supplier-dominated sectors**

To elaborate the third point (transfer of knowledge and innovations to incumbent actors), we build on the sectoral system of innovation (SIS) approach. Knowledge flows are particularly important in supplier-dominated sectors, which are characterised by a division of innovative labour, with universities, government institutes or specialised suppliers doing formal R&D, and firms doing the actual implementation. The reason for this division of roles is that firms in supplier-dominated sectors are usually small, and do not have the capability or resources to perform formal research. The division of labour does not mean that small firms are passive recipients. Because the actual systems are ‘distributed’ or ‘configurational’, it involves ‘work’ to align the multiple components in a system, especially when they are new. While individual component innovations can be tested in a research laboratory, concrete implementation entails ‘learning by trying’ (Fleck 1994). The feedback of hands-on implementation experiences to actors who perform formal R&D is an important process in sectoral innovation systems (Malerba 2002). The SIS approach, which sees innovation as a collective multi-actor process, therefore emphasises network interactions and bi-directional flows instead of one-directional linear flows from universities to firms.

While SIS is useful for addressing knowledge and innovation flows, Geels (2004) argued that a better conceptualisation of institutions was needed, because these coordinate and influence the social activities on which knowledge flows depend. Expanding on the SIS approach, he therefore distinguished three main dimensions: (1) knowledge and technology, (2) actors and networks, (3) institutions. Building on institutional theory (Scott 1995), he further distinguished regulative, cognitive and normative institutions. Examples of regulative institutions are laws and regulations. Examples of cognitive institutions are belief systems, problem agendas, guiding principles and search heuristics. Examples of normative institutions are role relationships, behavioural norms

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and social attitudes. These institutions have positive or negative influences on interactions and knowledge flows within social networks.

Because of the division of innovative labour, knowledge and innovation flows are a crucial mechanism for transitions in supplier-dominated sectors. We will empirically investigate this mechanism in Section 4, analysing the knowledge flows in post-war Dutch greenhouse horticulture. We expect that the specific networks and institutions help explain the speed of the Dutch transition.

### 3. The reconfiguration of Dutch greenhouse horticulture (1930–1980)

This section makes an ‘outside-in’ analysis of the overall transition pattern, focusing on the interaction between the greenhouse system and emerging novelties. The analysis is divided into three periods: (1) emerging novelties in the context of a stable system (1930–1945), (2) adoption of new elements into the greenhouse system (1945–1960), (3) system reconfiguration and performance improvements (1960–1980).

The analysis has a techno-economic focus, because supplier-dominated sectors are characterised by price sensitive consumers and firm orientation towards cost-cutting innovations (Pavitt 1984). We will therefore focus on technical bottlenecks, markets dynamics, innovation processes and price/performance improvements and how these influence the transition pattern. In terms of crops, we focus on tomatoes, the dominant greenhouse product for the 1930–1980 period.

Empirical data come from secondary sources and from primary research in the National Archives of the Department of Agriculture (Horticultural Directorate (HD), National Agency for Horticultural Economics (NAHE)), The archives of the Municipality of Naaldwijk and the Westland Museum — were regional horticultural newspapers were studied as well as correspondence between local government and companies — and company archives of the horticultural company ‘New Honsel’ (in the Municipal Archives of The Hague), the vegetable and fruit processing companies ‘Hero’ (in the Provincial Archives in Den Bosch) and ‘De Betuwe’ (in the Regional Archives in Tiel).

#### 3.1. Emerging novelties in the context of a stable system architecture (1930–1945)

##### *The ‘Westland greenhouse’ system*

The ‘Westland greenhouse’ originated from Guernsey, the British Channel Island with important horticultural commerce (Harvey, Quilley, and Beynon 2002) and appeared in the Netherlands around 1910. While existing ‘grape greenhouse’ designs were designed for mono-crops, the ‘Westland greenhouse’ was more versatile and suited for various crops (Figure 4). The ‘Westland

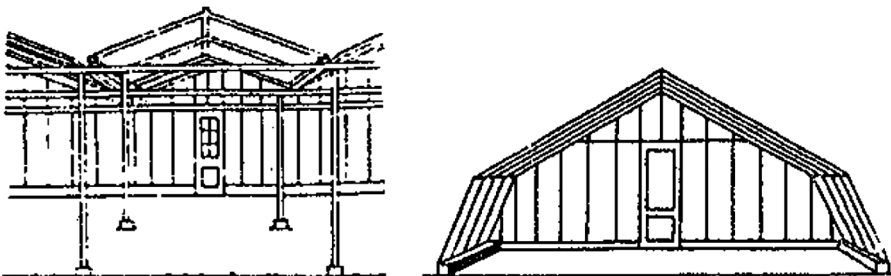


Figure 4. ‘Westland greenhouse’ (left) and ‘grape greenhouse’ designs (Vijverberg 1996).



greenhouse' diffused rapidly between 1910 and 1930, piggybacking on expanding tomato sales (Van den Muijzenberg 1980).

The 'Westland greenhouse' design was a technical improvement over closed glasshouse designs, which experienced problems of soil dehydration and accumulating salt concentrations, as explained by an horticultural manual in 1933:

For soil that is situated high above groundwater, the upper layer dehydrates so much, that it cannot be moisturized by sprinkling only. After repeated rainfalls only — usually occurring in November and December — the original moisture can be restored. (Quoted in Vijverberg 1996, 57)

In 'Westland greenhouses' the top glass plates could be removed, especially during winter months, allowing rains to flush the soil and improve fertility, but the removable glass plates also increased draught and increased the risk of plant diseases (Vijverberg 1996).

Early greenhouse farming was close to open-air horticulture, because of dependence on natural inputs and influences, e.g. sunlight for growth and heat, manure for fertilising, and rain for periodic flushing. Daily watering, however, was done with hoses or buckets, which was labour-intensive work.

Government involvement was limited to funding the ERE-triptych (education, research, extension). This changed in the 1930s, because the economic crisis ravaged horticulture, with export volumes of vegetables more than halving between 1929 and 1935 (Bieleman 1992). The price for tomatoes plummeted from 25.58 guilders in 1930 to 9.54 guilders 1935 (National Archives, HD no. 232). The government stepped in to help farmers survive the crisis by providing interest-free loans and direct income support. To combat over-production and decreasing prices, the government also set production restrictions. The scale of government support was massive. Between 1933 and 1936, total expenditures of the Agriculture Crisis Fund were 200 million guilders per year (Bieleman 1992). Horticulture in the Westland, the largest horticultural area in the Netherlands, situated between The Hague and Rotterdam, received about 23 million guilders as direct government support.

Agricultural markets gradually recovered during the late 1930s. The tomato price, for instance, gradually increased from 10.69 guilders in 1936 to 25.68 in 1939 (National Archives, HD no. 232). But the financial position of many farmers remained fragile. Hence, innovations that had been developed in previous years (see below), were limitedly adopted. Farmers only implemented incremental changes to the 'Westland greenhouse', e.g. decreasing the size of construction elements, increasing the size of glass plates, placing top glass plates in more tilted positions towards the sun. These changes aimed to enhance natural light penetration in greenhouses, which stimulated growth rates and yields (Van den Muijzenberg 1980). Also the influence of different glass variations on sunlight penetration was investigated.

### *Techno-scientific novelties*

More radical innovations were developed in laboratories and industrial firms. Artificial light and irradiation of plants, for instance, was investigated by Philips, in a collaborative 1928 research project with Wageningen Agricultural University, the electro-technical industry, electricity companies and standardisation committees (Boersma 2004). This innovation promised to lengthen the daily light period which would stimulate plant growth. Horticulture might thus become a possible market niche for special electric lights. The Horticultural Experimental Station in Naaldwijk tested Osram lamps, Vitalux lamps and Neon tubes in real-life greenhouses (Barendse 1949; Boersma 2004). These tests showed that heat production from the lamps was a significant problem, which

required precision control of the light-temperature ratio. Artificial lighting did not diffuse widely in the 1930s because of these operational problems and because of difficult economic conditions. In the late 1930s, Philips therefore terminated the research project (Stender 1964).

Artificial heating was also investigated. In 1910, the Horticultural Experimental station for the Westland tested coal and cokes burners that heated water, which was disseminated through greenhouses with pipes and radiators (Stender 1964). On the one hand, higher temperatures stimulated growth rates and crop yields, and enabled extension of the growing season, allowing more yields per year. On the other hand, artificial heating led to additional purchase and fuel costs, and additional labour costs, because coal burners required skilled operators and regular maintenance. Careless heating could also lead to temperature fluctuations, which enhanced disease receptiveness. Much heat was lost through cracks around the removable plates of 'Westland greenhouses'. Because of these economic and operational difficulties, artificial heating was only used limitedly in the 1920s and 1930s. Only large horticulturalists with sufficient personnel and skills, such as 'New Honsel', a pioneering firm in greenhouse tomatoes, experimented with heated glasshouses (New Honsel Company Archives, no. 1).

Research also focused on soil conditions and fertility, in particular artificial fertilisers, based on chemical combinations of phosphates or sulphates. In the 1930s, the Soil Laboratory of the Westland Experimental Station (in Naaldwijk) tested fertiliser compositions for different crops, discussing the findings with Wageningen Agricultural University and chemical factories such as Delftsche Gist-en Spiritusfabriek (Barendse 1949). Soil researchers also addressed the problem of high salinity that turned parts of the greenhouse soil into 'dead' spots. The removable glass plates of the 'Westland greenhouse' formed one response to this problem (providing periodic flushing in rainy periods), but this design was leaky, windy and led to heat loss. Hence, researchers began investigating other solutions such as above-ground sprinkling systems and underground drainage technologies (Vijverberg 1996).

### **3.2. Diffusion and adoption of new elements into the system (1945–1960)**

#### *Developments in the existing system*

War damage to greenhouse farming was substantial, with 1,786,300 m<sup>2</sup> of horticultural glass being broken or damaged. Greenhouse reconstruction to the level of 1939 would require 900,000 m<sup>2</sup> glass plates, 568,000 m<sup>2</sup> small glass plates, 1,670,000 window frames, 175,000 m of heating pipes, 30,000 m of narrow-gauge railway, 400 central heating boilers and 500 motor pumps (Van Doesburg et al. 1999; Dekker 1964). Investments in the immediate post-war years were allocated to these basic repairs, not to major innovations. This was also due to uncertain economic prospects in the late 1940s.

Changes in greenhouse farming were stimulated by: (1) 'pull factors' such as enhanced market demand, market liberalisation and export, (2) changing economic incentives (rising labour costs) and (3) changing government policies. We first discuss these contextual changes and then turn to greenhouse farming.

In the 1950s, economic conditions and market demand improved. The 'German economic miracle' translated into foreign consumer demand for horticultural products. Between 1950 and 1960, German tomato imports more than quadrupled from 53,000 tons to 222,572 tons, with Dutch horticulturalists increasing their market share from 40% to 51% because of enhanced competitiveness. For Britain, the second Dutch export market for tomatoes, exports increased from 15,000 to 37,000 tons between 1950 and 1960, with Dutch farmers increasing their market share from 8% to 16% (Gijssberts 1964).

These foreign exports were stimulated by trade liberalisation. In the immediate post-war years, bilateral trade treaties regulated and constrained horticultural exports. The trade in greenhouse vegetables and fruits was limited, because they were seen as luxury products. In 1949, a trade and clearings treaty with West Germany created new export opportunities for Dutch vegetables and fruits. The Common Agricultural Policy (1958) further opened the European markets for agricultural products and Dutch farmers were quick to take advantage. Other government regulations, which often originated from the 1930s crisis, were abolished in the post-war decades. Guaranteed minimum prices for vegetables and fruits were stopped in 1948 (Bieleman 1992). In 1949, the government relaxed the system of growing permits, providing space for horticultural expansion. Production licenses were particularly granted to farmer's sons. Because little land was available for arable or dairy farming, these farmer's sons often turned to intensive forms of agriculture, such as greenhouse horticulture.

Domestic demand for agricultural products also grew, as Dutch national income increased almost 200% between 1950 and 1970. Greenhouse farming was further stimulated by consumer preferences, which changed from cheap, nutritious vegetables, such as cabbages, to lighter, more refined and more expensive vegetables, often grown in greenhouses (Gijsberts 1964). Tomatoes increasingly appeared on the menu, in salads or accompanying meat, and were also increasingly used by food industries in processed foods such as spaghetti sauces, tomato soups and drinks (tomato juice). Table 2 demonstrates the rapid growth in the Dutch export and domestic consumption of tomatoes during the 1950s, making it into the symbol of a modern and innovative Dutch horticultural sector. Lettuce and other fruits from heated greenhouses also benefited from the new export opportunities, but grapes experienced decline in the 1950s, because of increased competition from Southern European countries.

Rising wages increased labour costs, which created a supply-side incentive for the shift from labour to capital (Bieleman 1992). To increase labour productivity, innovative farmers increasingly invested in machines and technologies. The trend towards mechanisation enabled farmers to work larger plots of land and increase their production. Greenhouse farmers, who faced strong competition from Southern European countries in export markets, also invested in new technologies to stimulate their productivity and competitiveness.

Farmers were hesitant, however, because the shift to mechanisation and rationalisation required a new mentality of entrepreneurship (Defares 1986). Farmers were used to invest money they had previously saved, to reduce dependence on banks and survival risks during economic downturns. The new era of mechanisation, however, required them to borrow large sums of money from banks. This, in turn, required them to make investment plans, and learn economic planning and bookkeeping. The government, agricultural schools and extension services played important roles in this learning process (see below).

Table 2. Markets for main Westland horticultural products, 1939–1960 (data from Gijsberts 1964).

	Export (tons)			Interior consumption (tons)		
	Tomatoes	Grapes	Lettuce	Tomatoes	Grapes	Lettuce
1939	32,970	6600	18,650	4670	9860	19,610
1946	14,970	6010	10,050	18,920	8310	33,090
1950	41,220	7610	12,770	18,700	7410	27,540
1951/53	71,600	6200	17,500	18,100	6800	28,500
1960/62	179,500	2000	43,900	29,600	8700	35,200

Governments also stimulated borrowing and investments by providing payback guarantees to banks on the loans they provided to farmers. In 1963, the government introduced the Development and Buy Out Fund, which provided subsidies to innovative farmers who want to mechanise and expand, and compensated small farmers who wanted to discontinue their business (Van den Brink 1990). This measure thus stimulated agricultural investments, scale increases and take-overs.

Modernisation and mechanisation were further promoted with regional improvement projects, which subsidised 50% of the costs of new technologies (Van den Brink 1990). By reducing the risks of investment decisions, these projects also aimed to stimulate early diffusion, learning processes and imitation effects.

### *Diffusion and adoption of novelties into the greenhouse system*

In these changing economic and policy contexts, new component innovations, which had emerged in the previous period, gradually entered the greenhouse system. This process was stimulated by price/performance improvements in these components, their competitive benefits for farmers and their problem-solving potential.

Oil-fired heating entered greenhouses in the early 1950s. Oil stoves were cheaper than coal stoves, which had been tried in the pre-war period. They also required less maintenance and were easier to operate (turning the oil tap was easier than shovelling coal into furnaces). Before 1950, tomatoes were only grown during the summer-season in unheated greenhouses. The introduction of oil heating enabled longer growing seasons, which stimulated the competitiveness of Dutch farmers compared with Southern European farmers, who had the natural benefit of warmer climates. Artificial heating not only created higher temperatures, but also extended the growing season by several months (New Honsel Company Archives, no. 1; Van Soest 1964). Together with artificial lighting it even created the promise of year-round crops.

The attitudes of greenhouse farmers towards artificial heating were generally positive. Boilers and pipes became symbols of modern and entrepreneurial farming (Vijverberg 1996). More pipes and chimneys and larger areas of glass signified higher social standing. This is illustrated by an anecdote from 1954, reported by Oudshoorn (1957), about a horticulturist from Poeldijk, a city in the Westland, who did not appear at his daughter's wedding, because his son in law was the son of a horticulturist with fewer pipes.

While artificial heating implied additional fuel costs, higher productivity during more months led to increased production and higher revenues. Operation of heating installations was further simplified by the introduction of automatic heat and temperature regulation devices, which also meant less temperature fluctuations than with coal burners. Heating technology suppliers and the Horticultural Experimental Station in Naaldwijk also worked on more efficient boilers and heat distribution systems that would reduce fuel costs. The Experimental Station also provided technical and economic advice to horticulturists with regard to greenhouse heating. A 'fuel-economy' consultant provided dedicated heating courses for farmers (Stender 1964). Between 1954 and 1964 the area of heated greenhouses in the Westland increased from 30% to 50% (Dekker 1964).

Steam, which was generated through artificial heating, was also used for new methods of soil disinfection, which combated soil-diseases and fungi. This was facilitated by new synthetic materials which enabled horticulturists to release steam under large soil areas covered with heat-resistant plastic sheets.

Artificial lighting returned on the agenda in the late 1940s, when Philips restarted its agricultural research programme into relations between artificial light and crop growth (Boersma 2004).

While some greenhouse farmers adopted fluorescent tubes in the mid-1950s, high costs and uncertainties about performance effects hindered wider diffusion. During the 1960s and 1970s researchers from Philips and the Institute for Horticultural Engineering worked on performance improvement and reduced costs (National Archives, NAHE, no. 15), but it was not until the 1980s that artificial light became widespread for certain crops, especially flowers (Van Doesburg et al. 1999). While artificial lighting remained difficult, horticulturalists did adopt incremental innovations that enhanced the inflow of natural light, e.g. new glass qualities with better light distribution qualities and new greenhouse designs with wider glasshouses, more glass and less support beams (Van den Muijzenberg 1980).

Artificial watering was an important labour-saving device. Because watering by hose or bucket was labour-intensive, horticulturalists adopted spray systems with electric pumps in the mid 1950s (Vijverberg 1996). The addition of automation, via control panels and electric taps, further reduced labour demands and enabled the tailoring of water supply to particular crop needs (Van Doesburg et al. 1999).

Artificial water systems also facilitated periodic soil flushing that prevented salt accumulation. The combination of flushing with underground drainage systems led to improved soil desalinisation, which expanded the variety of crops that greenhouse farmers could grow. In the late 1950s, lettuce, a salt-sensitive crop, could be produced all year round, making it the second most important greenhouse crop, after the tomato (Van Soest 1964).

Greenhouse horticulture also benefited from biological innovations. Advances in breeding produced new tomato varieties tailored to particular (seasonal) conditions. Pale varieties, such as the Victory, gradually replaced traditional breeds such as Ailsa Craig and Tuckwood. Improved breeding techniques also influenced other crops such as cucumbers and produced lettuce varieties for different seasons (Van Soest 1964).

### **3.3. System reconfiguration and performance improvements (1960–1980)**

While the component innovations entered the greenhouse as ‘modular innovations’, learning processes and knock-on effects led to new combinations and further changes in the design architecture of greenhouse systems. These reconfiguration processes transformed both the technical characteristics of greenhouses and the farming practices, which changed from craft-based farming to technical entrepreneurship. They also boosted the techno-economic performance of Dutch greenhouse farming, making it into a world leader.

One knock-on effect of artificial heating was CO<sub>2</sub> fertilisation. Farmers learned that the burning of fossil fuels enhanced CO<sub>2</sub> concentrations, which in turn stimulated plant growth. Researchers developed methods to increase CO<sub>2</sub> concentrations to 0.1% (instead of the normal 0.03%). In the early 1960s horticulturalists therefore began burning additional propane gas or paraffin, releasing the exhaust gases in the greenhouse (Stender 1964).

Another knock-on effect of artificial heating was air pollution, caused by the burning of fuel oil. Soot deposits on glass surfaces hindered natural light penetration in greenhouse farming, while soot deposits in residential neighbourhood soiled the laundry, cars and houses and damaged the public image of greenhouse farming. Researchers therefore began to investigate alternatives such as natural gas, which caused less air pollution (National Archives, NAHE, no. 15). This research was stimulated by the discovery of large natural gas reserves in 1959 (Correljé, Van der Linde and Westerwoudt 2003). The Institute for Horticultural Technology (IHT), the Dutch Gas Union, the Gas Institute and manufacturers of gas burning technologies investigated whether existing oil furnaces could be retrofitted to burn natural gas. Although technical results were

promising, a 1966 report from the IHT concluded that ‘across the board gas appears to be more expensive than oil’ (National Archives, NAHE, no. 15). Nevertheless, the government pushed for gas-fired greenhouse farming (Van Doesburg et al. 1999). Because nuclear energy was expected to become the most important energy source, natural gas reserves had to be consumed before nuclear energy kicked in (Correljé, Van der Linde, and Westerwoudt 2003). When researchers found that gas burning facilitated CO<sub>2</sub> fertilisation, the government used this as an additional argument to stimulate the shift to natural gas. The government used its power as major shareholder in the Dutch Gas Union to facilitate this shift by ensuring low gas tariffs for greenhouse farmers:

To further boost the use of natural gas in horticulture and greenhouses, a special arrangement (1970) provided these users with low-priced gas. They were offered a much cheaper tariff than normal consumers. In a strongly coordinated campaign, the sector converted quickly to gas. By 1972 gas supplied around 50% of the sector’s energy requirements. Particularly in western parts of the country, the reduction of oil use in greenhouses contributed to a decline in smog. (Correljé, Van der Linde, and Westerwoudt 2003, 66)

The supply of cheap gas also lowered fuel costs and stimulated the international competitiveness of greenhouse horticulture.

A third knock-on effect of artificial heating was the emergence of new diseases, related to higher temperatures and extended growing seasons. Mildew, a fungous infection of the leaves, began to plague greenhouse tomatoes. Other common diseases were kurkwortel, a soil-disease that affected the roots, and blossom end rot. These problems triggered innovation responses. Scientists developed pest-control, disease suppressing chemicals and tried to graft tomato varieties onto resistant rootstocks (Van Soest 1964). More difficult to combat were the tomato mosaic virus and botrytis, which both occurred at high humidity. Farmers therefore tried to prevent diseases by increasing the frequency of steam soil disinfection and disease testing of soil and crops. The number of soil tests sent to the Horticultural Experimental Station increased from 15,000 in 1965 to 50,000 in 1975 (Van Doesburg et al. 1999).

As new component innovations entered greenhouses, farmers recognised drawbacks in ‘Westland greenhouse’ design. Because these greenhouses had leaks and cracks around the removable top plates, they hindered artificial heating, CO<sub>2</sub> fertilisation and ground steaming from reaching their full potential, because of heat loss and CO<sub>2</sub> dissipation. In the early 1960s, ‘Westland greenhouses’ therefore came to be seen as a straightjacket, a bottleneck for further modernisation. This stimulated a shift to the ‘Venlo greenhouse’ design with isolated, closed and fixed-glass rooftops (Stender 1964). This design had emerged in the 1930s in the Southeast of the Netherlands. In this hilly terrain, downhill drainage automatically washed salt from the greenhouse soil (Vijverberg 1996). Horticulturalists could therefore use closed, fixed-glass rooftops without encountering the normal salt accumulation problems. In the 1960s, the ‘Venlo greenhouse’ design could be transferred to the Westland, because water sprinkling, flushing and drainage systems had solved the salt accumulation problem on flat terrains. These technical innovations thus made the removable glass plates of the ‘Westland greenhouse’ redundant.

The shift resulted in completely closed, isolated systems that were independent of natural fluctuations. Artificial heat, artificial light, fertiliser, pest control and watering systems transformed greenhouse horticulture into a year-round artificially controlled vegetable factory, with new farming practices that saw farmers work as production managers and machine operators. It allowed the tomato to change from a summer treat to a year-round product. Associations with industrial

centres were reinforced by the expansion of chimneys and by specialisation with farmers focusing on single crops. In a 1964 memorial book, one of the authors complained about this loss of variety:

In 1940, a single company of 2 to 3 hectares often produced blue and white grapes, peaches, plums, endive, tomatoes, sprouts, cauliflower, onions, berries, and maybe had some pigs, chicken, rabbits and a single cow on the side. Nowadays, it is lettuce and lettuce again or one sees a forest of tomato plants. (Oudshoorn 1964, 107)

The new Venlo greenhouse design was versatile and stimulated diversification. While tomatoes remained important, other crops such as lettuce and cucumber were also increasingly grown in Venlo greenhouses. After 1970, greenhouse farmers increasingly turned to the premium market of flowers and pot plants.

Technical greenhouse components were improved in the 1960s and 1970s as the Wageningen Institute for Horticultural Engineering focused R&D projects on further mechanisation and rationalisation. In 1960, the Institute investigated ‘improved methods and organization in vegetable growing in greenhouses’ (project no. 193). In 1965, it started projects that studied ‘Mechanical pollination of tomato flowers’ (project no. 259) and ‘Transport systems in greenhouses’ (project no. 265). In 1966, new projects investigated ‘Automated ventilation in greenhouses’ (project no. 271) and ‘Mechanization of vegetable growing in greenhouses’ (project no. 273) (National Archives, NAHE, no. 15).

The changes in technical hardware, greenhouse design, farming practices and crop varieties resulted in major performance increases. Tomato productivity (kg/ha), for instance, almost doubled between 1960 and 1980 (Figure 5).

Cheap gas, higher labour productivity and lower fixed assets also lowered relative production costs (guilders per kg) by almost 70% for tomatoes between 1954 and 1975 (Figure 6). These cost/performance improvements enabled Dutch greenhouse crops to compete internationally with Southern European countries.

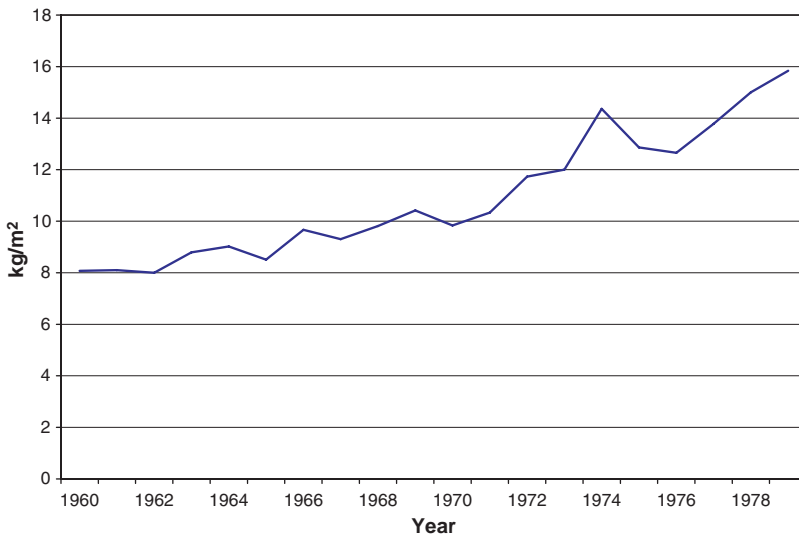


Figure 5. Increases in Dutch productivity and tomato yields (kg/m<sup>2</sup> per year). Data from the Food and Agriculture Organization, [www.fao.org](http://www.fao.org) (accessed 3 February 2008).

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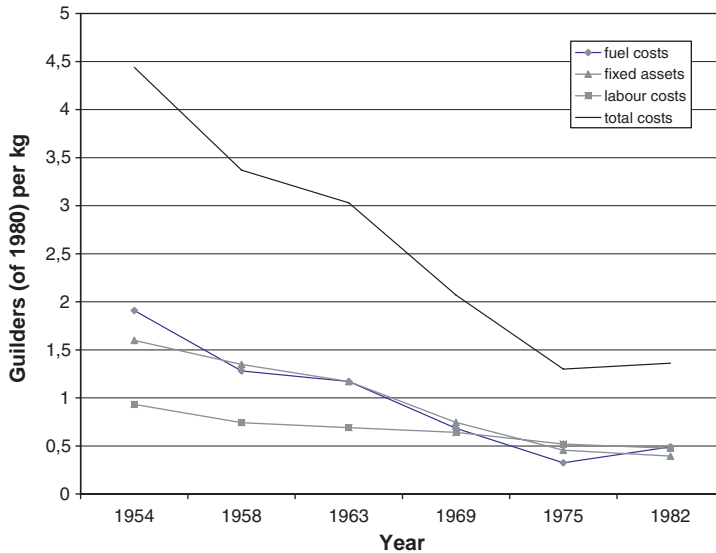


Figure 6. Relative production costs for tomatoes (1980 guilders/kg) (data from Buurma 2001, 21).

#### 4. Network interactions and knowledge flows

To complement the preceding ‘outside-in’ analysis, which had a techno-economic focus, this section makes an ‘inside-out’ analysis, focusing on social networks and institutions that influenced the knowledge flows in the sectoral innovation system. The efficient functioning of this system explains to a large degree the speed of adoption of innovations in Dutch greenhouse farming.

##### 4.1. Social networks

The social networks within the horticultural community were strong and deep, creating an economic cluster. These networks first emerged in the early twentieth century, when individual horticulturists created cooperatives to strengthen their negotiation position *vis-à-vis* buyers of fruits and vegetables. In subsequent decades, these cooperatives were extended to interactions with suppliers of seeds, fertiliser and equipment. In the late 1960s, the cooperatives also negotiated favourable contracts with gas suppliers, although backed up by government support.

While cooperatives were initially driven by commercial interest, they stimulated social interactions that helped create a collective identity and open attitude towards their own community (Vijverberg 2004). Large horticulturalists, who engaged in their own technical experiments (e.g. New Honsel), were therefore willing to share their experiences and knowledge with other farmers (see Naaldwijk Municipality Archives, *Westlandsche Courant* (‘Westlands Newspaper’)).

The willingness to learn also led to the creation of horticultural study clubs, which organised meetings and courses in the winter-season. In the two post-war decades, 17 study groups were set up in the Westland area with more than 3000 members (Scholten and Sonneveld 1999). The study clubs drew in external expertise, inviting researchers and extension service officials to give presentations. The study clubs also set up their own experiments with new crop varieties and cultivation systems and organised excursions to innovative farmers and demonstration projects. The creation of the Dutch Federation of Horticultural Study Clubs, in 1964, signalled formal recognition of



their importance for the horticultural innovation system (Buurma 2001). Researchers from the experimental stations and Wageningen Agricultural University increasingly interacted with these study clubs, because their 'crop committees' provided valuable feedback on the basis of real-life testing (Van Doesburg et al. 1999).

The auction system further stimulated the collective identity of horticulturalists. These auction systems graded tomatoes (and other products) in terms of size and quality categories, without differentiating in terms of producers. Because products were thus sold *en bloc*, farmers had a collective interest in product quality improvements (Vijverberg 1996). This stimulated the willingness to exchange lessons and experiences.

The ERE-triptych (education, research and extension) strongly influenced the university–industry knowledge flows.

Transfer of knowledge, skills and technologies to the farming community was primarily a matter for the Agricultural Extension Service, the agricultural experiment stations and lower-level agricultural schools. A major function of the Wageningen school became providing competent agriculturists for these services. (Maat 2001, 107)

In the post-war modernisation ideology, the network relations in the ERE-triptych were seen as a linear model, with Wageningen Agricultural University producing scientific knowledge that was subsequently transferred to farmers. In reality, however, and in line with recent insights about sectoral innovation systems (e.g. Malerba 2002), there were mutual feedbacks and exchanges in this knowledge system. A three-tier distribution of innovative labour emerged: (1) researchers at the university and technical institutes (e.g. Institute for Horticultural Technology) developed theoretical knowledge, (2) Horticultural Experiment Stations developed practical knowledge in test circumstances, and (3) local farmers and horticultural study clubs produced real-life knowledge, based on experiences in a variety of concrete greenhouse practices. Instead of a one-way flow, the innovation system was thus multi-sited with multi-directional interactions.

Knowledge also flowed via circulation of individuals (embodied knowledge). Researchers from the Dutch organisation for Applied Scientific Research were, for instance, posted at the horticultural experimental stations in Aalsmeer and Naaldwijk (Scholten and Sonneveld 1999). University researchers were sometimes posted with extension services. Research institutes paid for university chairs in particular areas and university professors set up commercial research institutes. Maat (2001) therefore concludes:

The organization of agricultural research in the Netherlands developed ... into a layered structure, divided over the departments and laboratories of the Agricultural University, the research institutes and the experiment stations. ... The research performed at the Agricultural University could present itself as fundamental without losing its agricultural identity only when a clear relation was maintained with divisions that performed the more applied research. (91–3)

Although greenhouse farmers did little formal R&D, these networks and interactions made greenhouse farming into an effective innovation system.

#### 4.2. Institutions

Cognitive, regulative and normative institutions also influenced innovation and knowledge exchange. An important cognitive institution was a relative consensus about new goals and visions for agricultural modernisation. Following the shock of the Second World War, the four main goals

were (Van den Brink 1990): (1) food security: reliable and sufficient food supply ('no more hunger'), (2) cheap food supply: low food prices would allow low wages, which would stimulate industrialisation, (3) reasonable incomes for farmers (guaranteed livelihood), (4) increased export, so that agriculture would improve the national balance of payments. To achieve these goals, the government and national farmer associations developed a vision of agricultural modernisation, which centred on rationalisation, mechanisation and scale increase. The shared belief in this vision provided direction to investments and stimulated the will to innovate.

Knowledge exchange was also promoted by a congruence in mindsets between farmers and university researchers. Because most agricultural researchers came from farming families, they had intimate knowledge of concrete farming practices to which they could tailor their findings (Van den Brink 1990). Nevertheless, farmers were often sceptical and not easily persuaded by purely scientific arguments. This perception led to an innovation pattern with much emphasis on demonstration projects and concrete experiments, with the horticultural experimental stations and study clubs playing crucial intermediary roles.

A regulatory institution that was crucial for university–industry knowledge flows was the ERE-triptych, which substantially expanded in the post-war decades (Van den Brink 1990). The number of employees at the Agricultural Extension Service tripled in 10 years, from 500 in 1946 to 1420 in 1950 to 1580 in 1956 (Zuurbier 1984). Extension experts gave presentations for farmers, visited study clubs, distributed reports, and organised excursions to model farms. While the information initially focused on new technological possibilities, economic and investment information gradually became more important. A similar change occurred in the expanding number of agricultural schools, which between 1950 and 1960 increasingly paid attention to book-keeping and agricultural entrepreneurship (Van Doesburg et al. 1999). The Horticultural vocational school in Naaldwijk, for example, introduced courses in 'Horticultural economy', 'Commercial correspondence' and 'English'. By disseminating new practices regarding money and investing, agricultural schools and extension experts helped to transform farmers into entrepreneurs who borrowed money from banks if cost–benefit calculations of investment decisions were positive (Bieleman 1992).

Other important regulatory changes were the abolishment of import and export restrictions, guaranteed minimum prices, production licenses, etc. The liberalisation of production, trade and export stimulated Dutch horticulture, which greatly depended on exports. Bank guarantees for loans, regional development projects, and the Development and Buy Out Fund were also regulatory actions that stimulated the production and diffusion of innovations.

Important normative institutions were collective entrepreneurship (through cooperatives) and trust, which were stimulated by social ties that originated from intermarriage and kinship relations. Westland horticulturists did not see each other as competitors but as colleagues — part of collective enterprise. A Protestant work ethic further stimulated norms of hard work and a desire to improve (Defares 1986; Vijverberg 2004). A willingness to learn and share experiences further led to a collective innovation pattern for the Westland horticultural cluster as a whole.

## 5. Conclusions

The article has contributed a new case study to the literature on technological transitions. This case was selected from the supplier-dominated category in Pavitt's innovation typology. The case study did not follow the substitution pattern, which was found in previous cases from other sectoral innovation categories (scale intensive, science-based, government/utilities). Instead, the greenhouse transition followed a stepwise reconfiguration pattern that matched the three characteristics

described in Section 2: (1) the transition involved multiple component innovations that were first developed by universities, research institutes and technology suppliers, and subsequently adopted in the greenhouse system, (2) these innovations were initially incorporated as modular innovations (either as add-on or component replacement), and subsequently transformed the architecture and practice of horticulture, and (3) most of the existing greenhouse farmers survived and enacted the transition. The case study also confirms the plausibility of the three-phase pattern in reconfiguration transitions.

One qualification, however, is that the representation in Figure 3 is somewhat too simple, as it suggests that all relevant niche-innovations are developed in the first phase. This is not confirmed by the case study, which showed that some relevant innovations (e.g. the shift to natural gas) emerged in the second or third phase. Another qualification concerns the prediction that major performance improvements typically occur in the third phase. The case study does not corroborate this prediction, because it showed that productivity yields and production costs for tomatoes improved fairly gradually (Figure 5 and 6). Although the case study did confirm that reconfigurations culminated in a new system in the third phase, this does not apparently always lead to major performance shifts. This qualification fits with our thoughts on demarcation problems (Section 1), and the suggestion that reconfiguration transitions are more gradual and continuous change processes.

The reconfiguration pattern can be generalised to other cases that have two characteristics of supplier-dominated sectors. The reconfiguration pattern is likely in (1) other distributed systems where multiple often low-tech components work together, (2) sectors with a clear division of innovative labour, with universities or suppliers developing new innovations and firms adopting them into existing systems. In terms of external validity, we see no reason why these patterns would be limited to the Netherlands or to the 1930–1980 period. One qualification, however, is that the division of innovative labour was less prominent in pre-modern periods, when university research was more dissociated from practical innovation.

With regard to specific mechanisms, bi-directional knowledge flows are especially important in supplier-dominated sectors, because of the characteristic division of innovative labour. The analysis in Section 4 identified the social networks and institutions that influenced the speed of the horticultural transition.

We further identify ‘innovation cascades’ as crucial mechanism in reconfiguration transitions. This means that the adoption of innovations in an existing system leads to problems or creates opportunities that create fertile conditions for new innovations. At the system level, this mechanism creates cascades with innovations building on each other. The introduction of artificial heating, for instance, had several knock-on effects that triggered further innovation processes (in CO<sub>2</sub> fertilisation, disease control and reduction of soot emissions). Artificial heating and CO<sub>2</sub> fertilisation also created new problem perceptions, with the ‘Westland greenhouse’ design increasingly being seen as a ‘straightjacket’ that frustrated these innovations. But a shift to closed greenhouses (Venlo design), which would reduce this problem, was not possible until other solutions to soil dehydration, salinity and fertility problems were developed. Because artificial soil flushing systems and new fertilisers provided such solutions, they facilitated the transition to the Venlo design. We thus see an innovation cascade with different innovations building on each other: soil flushing systems + new fertilisers → shift to Venlo greenhouse design → further diffusion of artificial heating and CO<sub>2</sub> fertilisation. These ‘straightjacket dynamics’ and ‘innovation cascades’ help explain particular barriers and accelerations in transition processes.

Last, the case study shows that so-called ‘low-tech’ sectors are shot through with innovation dynamics. While most work in innovation studies focuses on high-tech sectors, the article thus

reminds us that innovation studies' insights can be usefully extended to 'low-tech' sectors such as retailing, banking, hospitals, airports and traditional manufacturing.

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## Notes

1. Pavitt (1984, 370) added this category to cover purchases by government and utilities of expensive capital goods related to defence, energy, communications and transport.
2. In fact, his CAPM case study in one firm did not work because of bugs and interface problems.

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