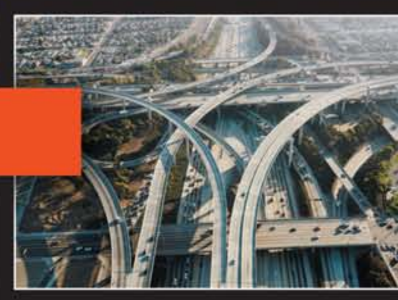
Logistics Engineering Handbook



Edited by G. Don Taylor

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This handbook is dedicated to my children, Alex and Caroline.

Alex always makes me laugh and he is the best pal I've ever had.
We think so much alike it seems that we are almost the same guy!
My time with him is treasured.

Caroline is the sweetest little person I've ever known.
She has stolen my heart forever and has made the word "Daddy"
my most cherished title.

Contents

Preface

Logistics activities are critical integrating functions in any type of business. Annual expenditures on logistics in the United States alone are equivalent to approximately 10% of the U.S. gross domestic product. Logistics expenditures represent an even larger percentage of the world economy. Thus, achieving state-of-the-art excellence in logistics functions, and attaining the inherent cost reductions associated with outstanding logistics efforts, is very important in terms of competitiveness and profitability. As logistics tools evolve in comprehensiveness and complexity and as the use of such tools becomes more pervasive in industry, it is increasingly difficult to maintain a position of leadership in logistics functions. In spite of the importance of the topic, logistics education often lags industry requirements, especially in terms of engineering-based needs. This handbook seeks to fill this void by providing a comprehensive reference tool that could be effectively used as an engineering textbook or as a complete and versatile professional reference.

This handbook provides comprehensive coverage of both traditional methods and contemporary topics in engineering logistics. It introduces the reader to basic concepts and practices in logistics, provides a tutorial for common logistics problems and solution techniques, and discusses current topics that define the state of the logistics market. The book is comprised of 30 chapters divided into 5 major sections. In each section, the reader will likely note that many of the chapters are written by leading experts in their field.

Although each major section of the book can be considered a stand-alone segment, the handbook is perhaps strongest when read or studied in the order presented. The first section, *Introduction to Logistics Engineering*, focuses on providing basic background information that defines the topic of engineering logistics. Chapters in this section discuss logistics from a historical perspective, discuss the economic impact of logistics functions, and introduce the reader to general logistics tools. Common metrics are discussed so that progress relative to logistics goals can be measured, and logistics is discussed from a system's perspective.

The second section on *Logistics Activities* delves into activities that commonly fill the workdays of logisticians. The section begins with chapters discussing important business-oriented issues like customer service, purchasing and sourcing. The section then provides chapters dealing with demand forecasting, facility layout and location, inventory management, material handling, warehousing, distribution networks and transportation systems management. The reader should find that the important chapter on facility layout and location is particularly comprehensive.

The third section is entitled *Topics in Transportation Management,* and goes into detail on issues related specifically to freight transport. Chapters discuss specific issues such as dispatching and pricing/rating in the trucking industry, but also provide information of more general interest, such as classic transportation problems, the management of freight imbalance, and yield management/capacity planning.

The *Enabling Technologies* discussed in Section IV of the book discuss those enabling technologies that are currently being exploited to great benefit in the logistics industry. Chapters include discussions of logistics tracking technologies, electronic connectivity techniques and software systems, and use of the Internet. Also included are a chapter on reliability, maintainability, and supportability in logistics systems, and a chapter discussing how logistics activities can be funded and justified.

Finally, the fifth section of the book deals with *Emerging and Growing Trends.* Chapters in this section deal with green logistics, reverse logistics and associated packaging needs, global logistics concerns, outsourcing, the use of third-party logistics providers, and the increasing reliance on intermodal transportation. Other chapters discuss the very timely topics of logistics in the service industry and the growing importance of securing the supply chain. This section makes the handbook particularly useful to savvy logistics professionals wishing to exploit possible future trends in logistics practice.

In spite of the growing importance of logistics as a necessary condition for business success, no comprehensive engineering-oriented handbook exists to support educational and reference needs for this topic. Although colleges and universities are starting to pay greater attention to logistics, business schools seem to be well ahead of engineering schools in terms of the development of educational materials, degree programs, and continuing education for logisticians. It is notable and telling that several of the contributing authors for this engineering-based handbook are business school professors. While business schools produce very capable logisticians, there is certainly also a great need for more technical logisticians, whether they come from industrial, systems or even civil engineering or related programs. This comprehensive *Logistics Engineering Handbook* is therefore needed to support education and reference needs for the more technically oriented logisticians. Although contributing authors do not, in the editor's view, make their chapters overly analytical, a more rigorous and mathematics-based treatment of many important topics has been encouraged.

If the engineering/technical orientation of the handbook is the key difference in comparison to other handbooks on the market, another distinguishing feature is that it provides an entire section dedicated more or less to freight transit. Even though transportation is the largest component of logistics expenses, the best engineering references seem to focus more on traditional issues such as plant layout and location, material handling, and classical transportation problems. This handbook covers those vital topics also, but offers an additional focus on transportation management and on freight transit in particular.

A final distinguishing factor for the handbook is that each chapter includes either a brief "case study" overview of an industrially motivated problem or a tutorial using fabricated data designed to highlight important issues. In most cases, this is a discussion that focuses on applications of one or more topics discussed in the chapter, in the form of either a separate section or as a "breakout" at the end of the chapter. In some cases, the case study environment is imbedded within the chapter so that key points can be illustrated with actual case data throughout the chapter. This feature of the handbook helps to ensure that the topics are relevant and timely in terms of industry needs. It also enables the reader to see direct application of the techniques presented in the chapters. Furthermore, having a required case study in every chapter served as a reminder to the contributing authors that the handbook has been designed to be a useful teaching and reference tool, not a forum for theoretical work.

The book should be equally useful as either a textbook or as part of a professional reference library. Beginning with the initial chapters, the handbook can be useful as either a course introduction or as a professional refresher. The comprehensive coverage of logistics activities and topics presented subsequently is likewise useful in either a classroom or business setting. Hopefully, the reader will agree that the chapters in this handbook have been written, in many cases, by the world's leading experts in their field and that the handbook provides a "one-stop shopping" location for logistics engineering reference materials ranging from basics, to traditional problems, to state-of-the-market concerns and opportunities.

About the Editor

G. Don Taylor, Jr. is the Charles O. Gordon Professor and Department Head of the Grado Department of Industrial and Systems Engineering at Virginia Polytechnic Institute and State University in Blacksburg, Virginia. In addition to leading this distinguished department, he has broad-based research interests in several aspects of logistics systems. He has particular interest in seeking state-of-the-art solutions to large-scale, applied logistics problems using simulation and optimization techniques. His recent work has been primarily in the truckload trucking and barge transportation industries.

Prior to joining Virginia Polytechnic Institute and State University, Professor Taylor held the Mary Lee and George F. Duthie Endowed Chair in Engineering Logistics at the University of Louisville where he was co-founder of a multi-university center, the Center for Engineering Logistics and Distribution. He has also held the rank of Full Professor at the University of Arkansas, where he was also the Arkansas Director of The Logistics Institute. He has held a visiting position at Rensselaer Polytechnic Institute and industrial positions at Texas Instruments and Digital Equipment Corporation.

He has a PhD in Industrial Engineering and Operations Research from the University of Massachusetts and MSIE and BSIE degrees from the University of Texas at Arlington. He has served as Principal Investigator (PI) or Co-PI on approximately 70 funded projects and has written more than 200 technical papers. This handbook is his eighth edited book or proceedings. He is a registered Professional Engineer in Arkansas and an active leader in the field of industrial and systems engineering.

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I

Introduction to Logistics Engineering

1

Logistics from a Historical Perspective

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1.1 Defining Logistics

Logistics is a word that seems to be little understood, if at all, by nearly anyone not directly associated with this professional and very important discipline. Many, when hearing someone say they work in the logistics field, associate it with some quantitative, technological, or mathematical practice. Some even confuse *logistics* with the study of language (i.e., *linguistics*). The fact is, logistics is a very old discipline that has been, currently is, and always will be, critical to our everyday lives.

The origin of the term logistics comes from the French word "logistique," which is derived from "loger" meaning quarters (as in quartering troops). It entered the English language in the nineteenth century.

The practice of logistics in the military sector has been in existence for as long as there have been organized armed forces and the term describes a very old practice: the supply, movement, and maintenance of an armed force both in peacetime and in battle conditions. Logistics considerations are generally built into battle plans at an early stage, for it is logistics that determine the forces that can be delivered to the theater of operations, what forces can be supported once there, and what will then be the tempo of operations. Logistics is not only about the supply of materiel to an army in times of war, it also includes the ability of the national infrastructure and manufacturing base to equip, support and supply the armed forces, the national transportation system to move the forces to be deployed, and its ability to resupply that force once they are deployed.

The practice of logistics in the business sector, starting in the later half of the twentieth century, has been increasingly recognized as a critical discipline. The first professional association of logisticians was formed in 1963, when a group of practitioners and academicians formed the National Council of Physical Distribution Management, which in 1985 became the Council of Logistics Management, and then in 2004 the Council of Supply Chain Management Professionals ("The Council"). Today, this organization has thousands of members around the world. A sister organization, The International Society of Logistics (or SOLE), was founded in 1966 as the Society of Logistics Engineers. Today, there are numerous professional associations throughout the world with essentially the same objectives: to conduct research, provide education, and disseminate knowledge for the advancement of the logistics discipline worldwide.

The Council, early on, recognized that there was confusion in the industry regarding the meaning of the term logistics. Over the years, they have provided, and adjusted to changing needs, a definition of logistics that is the most widely accepted definition worldwide. Just as important, they recognized that the relationship between logistics and supply chain management was not clearly understood by those who used these terms—often interchangeably. The Council struggled with the development of a broader definition of logistics and its' relationship to supply chain management that would be widely accepted by practitioners around the world. In 2003, the Council published the following definitions, and boundaries and relationships, for logistics and supply chain management:

1.1.1 Definition of Logistics Management

Logistics management is that part of supply chain management that plans, implements, and controls the efficient, effective forward and reverse flow and storage of goods, services, and related information between the point of origin and the point of consumption in order to meet customers' requirements.

1.1.1.1 Logistics Management—Boundaries and Relationships

Logistics management activities typically include inbound and outbound transportation management, fleet management, warehousing, materials handling, order fulfillment, logistics network design, inventory management, supply–demand planning, and management of third-party logistics services providers. To varying degrees, the logistics function also includes sourcing and procurement, production planning and scheduling, packaging and assembly, and customer service. It is involved in all levels of planning and execution—strategic, operational, and tactical. Logistics management is an integrating function, which coordinates and optimizes all logistics activities, as well as integrates logistics activities with other functions including marketing, sales manufacturing, finance, and information technology.

1.1.2 Definition of Supply Chain Management

Supply chain management encompasses the planning and management of all activities involved in sourcing and procurement, conversion, and all logistics management activities. Importantly, it also includes coordination and collaboration with channel partners, which can be suppliers, intermediaries, third-party service providers, and customers. In essence, supply chain management integrates supply and demand management within and across companies.

1.1.2.1 Supply Chain Management—Boundaries and Relationships

Supply chain management is an integrating function with primary responsibility for linking major business functions and business processes within and across companies into a cohesive and high-performing business model. It includes all of the logistics management activities stated earlier, as well as manufacturing operations, and it drives coordination of processes and activities with and across marketing, sales, product design, finance, and information technology.

1.2 Business Logistics and Engineering Logistics

Before moving on, it is probably helpful to understand the differences that exist between business logistics and engineering logistics. The fact is, there are few, if any, significant differences between the two except that logistics engineers are often charged with handling the more "mathematical" or "scientific" applications in logistics. For example, the business logistician might be concerned with building information systems to support supply chain management, whereas the logistics engineer might be looking for an optimal solution to a vehicle routing problem within defined time windows. This is important to understand as examples are provided throughout the remainder of this chapter.

1.3 Historical Examples of Military Logistics

Without supplies, no army is brave—Frederick II of Prussia, in his *Instruction for his Generals* 1747

Business logistics is essentially an offshoot of military logistics. So it behooves us to look at the military side of the logistical coin first. For war is not just about tactics and strategy. War is very often about logistics.

Looking at most wars throughout history, a point can be identified at which the victory of one side could no longer be prevented except by a miracle—a point after which the pendulum was tipped heavily to one side and spending less and less time on the other. Logistics is absolutely the main factor that tends to tip the pendulum. The following examples illustrate the importance of logistics in military campaigns of the past.

1.3.1 Alexander the Great

Alexander the Great and his father Philip recognized the importance and improved upon the art of logistics in their time. Philip realized that the vast baggage train that traditionally followed an army limited the mobility of his forces. In order to compensate he made the troops carry their own weapons, armor, and some provisions while marching, minimizing the need for a transportation infrastructure. Oxen and oxcarts were not used as they were in many other campaigns during earlier "ancient" times. Oxen could achieve a speed of only 2 miles per hour, their hooves were unsuitable for carrying goods for long distances, and they could not keep up with the army's daily marches, which averaged 15 miles per day. The army did not use carts or servants to carry supplies, as was the practice of contemporary Greek and Roman armies; horses, camels, and donkeys were used in Alexander's baggage train because of their speed and endurance. As necessary, road builders preceded the army on its march to keep the planned route passable.

Alexander also made extensive use of shipping, with a reasonable sized merchant ship able to carry around 400 tons, while a horse could carry 200 lbs (but needed to eat 20 lbs of fodder a day, thus consuming its own load every 10 days). He never spent a winter or more than a few weeks with his army on campaign away from a sea port or navigable river. He even used his enemy's logistics weaknesses against them, as many ships were mainly configured for fighting but not for endurance, and so Alexander would blockade the ports and rivers the Persian ships would use for supplies, thus forcing them back to base. He planned to use his merchant fleet to support his campaign in India, with the fleet keeping pace with the army, while the army would provide the fleet with fresh water. However, the monsoons were heavier than usual, and prevented the fleet from sailing. Alexander lost two-thirds of his force, but managed to get to a nearby port where he reprovisioned. The importance of logistics was central to Alexander's plans, indeed his mastery of it allowed him to conduct the longest military campaign in history. At the farthest point reached by his army, the river Beas in India, his soldiers had marched 11,250 miles in eight years. Their success depended on his army's ability to move fast by depending on comparatively few animals, by using the sea wherever possible, and on good logistic intelligence.

1.3.2 The Romans

The Roman legions used techniques broadly similar to the old methods (large supply trains, etc.), however, some did use those techniques pioneered by Philip and Alexander, most notably the Roman consul Marius. The Romans' logistics were helped, of course, by the superb infrastructure, including the roads they built as they expanded their empire. However, with the decline in the Western Roman Empire in AD fifth century, the art of warfare degenerated, and with it, logistics was reduced to the level of pillage and plunder. It was with the coming of Charlemagne in AD eighth century, that provided the basis for feudalism, and his use of large supply trains and fortified supply posts called "burgs," enabled him to campaign up to 1000 miles away, for extended periods.

The Eastern Roman (Byzantine) Empire did not suffer from the same decay as its western counterpart. It adopted a defensive strategy that, in many ways, simplified their logistics operations. They had interior lines of communication, and could shift base far easier in response to an attack, than if they were in conquered territory—an important consideration due to their fear of a two-front war. They used shipping and considered it vital to keep control of the Dardanelles, Bosphorous, and Sea of Marmara; and on campaign made extensive use of permanent magazines (i.e., warehouses) to supply troops. Hence, supply was still an important consideration, and thus logistics were fundamentally tied up with the feudal system—the granting of patronage over an area of land, in exchange for military service. A peacetime army could be maintained at minimal cost by essentially living off the land, useful for Princes with little hard currency, and allowed the man-at-arms to feed himself, his family, and retainers from what he grew on his own land and given to him by the peasants.

1.3.3 Napoleon in Russia

As the centuries passed, the problems facing an army remained the same: sustaining itself while campaigning, despite the advent of new tactics, of gunpowder and the railway. Any large army would be accompanied by a large number of horses, and dry fodder could only really be carried by ship in large amounts. So campaigning would either wait while the grass had grown again, or pause every so often. Napoleon was able to take advantage of the better road system of the early 19th century, and the increasing population density, but ultimately still relied upon a combination of magazines and foraging. While many Napoleonic armies abandoned tents to increase speed and lighten the logistics load, the numbers of cavalry and artillery pieces (pulled by horses) grew as well, thus defeating the objective. The lack of tents actually increased the instance of illness and disease, putting greater pressure on the medical system, and thereby increasing pressure on the logistics system because of the larger medical facilities required and the need to expand the reinforcement system.

There were a number of reasons that contributed to Napoleon's failed attempt to conquer Russia in 1812. Faulty logistics is considered a primary one. Napoleon's method of warfare was based on rapid concentration of his forces at a key place to destroy his enemy. This boiled down to moving his men as fast as possible to the place they were needed the most. To do this, Napoleon would advance his army along several routes, merging them only when necessary. The slowest part of any army at the time was the supply trains. While a soldier could march 15–20 miles a day, a supply wagon was generally limited to about 10–12 miles a day. To avoid being slowed down by the supply trains, Napoleon insisted that his troops live as much as possible off the land. The success of Napoleon time after time in Central Europe against the Prussians and the Austrians proved that his method of warfare worked. However for it to work, the terrain must cooperate. There must be a good road network for his army to advance along several axes and an agricultural base capable of supporting the foraging soldiers.

When Napoleon crossed the Nieman River into Russia in June 1812, he had with him about 600,000 men and over 50,000 horses. His plan was to bring the war to a conclusion within 20 days by forcing the Russians to fight a major battle. Just in case his plans were off, he had his supply wagons carry 30 days of food. Reality was a bit different. Napoleon found that Russia had a very poor road network. Thus he was forced to advance along a very narrow front. Even though he allowed for a larger supply train than usual, food was to be supplemented by whatever the soldiers could forage along the way. But this was a faulty plan. In addition to poor roads, the agricultural base was extremely poor and could not support the numbers of soldiers that would be living off the land. Since these 600,000 men were basically using the same roads, the first troops to pass by got the best food that could easily be foraged. The second troops to go by got less, and so forth. If you were at the rear, of course there would be little available. The Russians made the problem worse by adopting a scorched earth policy of destroying everything possible as they retreated before the French. As time went by, soldiers began to straggle, due to having to forage further away from the roads for food and weakness from lack of food.

The situation was just as bad for the horses. Grazing along the road or in a meadow was not adequate to maintain a healthy horse. Their food had to be supplemented with fodder. The further the army went into Russia, the less fodder was available. Even the grass began to be thinned out, for like food the first horses had the best grazing, and those bringing up the rear had it the worse. By the end of the first month, over 10,000 horses had died!

Poor logistics, leading to inadequate food supplies and increasingly sick soldiers, decimated Napoleon's army. By the time Napoleon had reached Moscow in September, over 200,000 of his soldiers were dead and when the army crossed into Poland in early December, less than 100,000 exhausted, tattered soldiers remained of the 600,000 proud soldiers who had crossed into Russia only five months before.

1.3.4 World War I

World War I was unlike anything that had happened before. Not only did the armies initially outstrip their logistics systems with the amount of men, equipments, and horses moving at a fast pace, but they totally underestimated the ammunition requirements, particularly for artillery. On an average, ammunition was consumed at ten times the prewar estimates, and the shortage of ammunition posed a serious issue, forcing governments to vastly increase ammunition production. But rather than the government of the day being to blame, it was faulty prewar planning, for a campaign on the mainland of Europe, for which the British were logistically unprepared. Once the war became trench bound, supplies were needed to build fortifications that stretched across the whole of the Western Front. Given the scale of the casualties involved, the difficulty in building up for an attack (husbanding supplies), and then sustaining the attack once it had started (if any progress was made, supplies had to be carried over the morass of "no-man's land"), it was no wonder that the war in the west was conducted at a snail's pace, given the logistical problems.

It was not until 1918, that the British, learning the lessons of the previous four years, finally showed how an offensive should be carried out, with tanks and motorized gun sleds helping to maintain the pace of the advance, and maintain supply well away from the railheads and ports. World War I was a milestone for military logistics. It was no longer true to say that supply was easier when armies kept on the move due to the fact that when they stopped they consumed the food, fuel, and fodder needed by the army. From 1914, the reverse applied, because of the huge expenditure of ammunition, and the consequent expansion of transport to lift it forward to the consumers. It was now far more difficult to resupply an army on the move. While the industrial nations could produce huge amounts of war materiel, the difficulty was in keeping the supplies moving forward to the consumer.

1.3.5 World War II

World War II was global in size and scale. Not only did combatants have to supply forces at ever greater distances from the home base, but these forces tended to be fast moving and voracious in their consumption of fuel, food, water, and ammunition. Railways proved indispensable, and sealift and airlift made ever greater contributions as the war dragged on (especially with the use of amphibious and airborne forces, as well as underway replenishment for naval task forces). The large-scale use of motorized transport for tactical resupply helped maintain the momentum of offensive operations, and most armies became more motorized as the war progressed. After the fighting had ceased, the operations staffs could relax to some extent, whereas the logisticians had to supply not only the occupation forces, but also relocate those forces that were demobilizing, repatriate Prisoners of War, and feed civil populations of often decimated countries.

World War II was, logistically, as in every other sense, the most testing war in history. The cost of technology had not yet become an inhibiting factor, and only a country's industrial potential and access to raw materials limited the amount of equipment, spares, and consumables a nation could produce. In this regard, the United States outstripped all others. Consumption of war material was never a problem for the United States and its allies. Neither was the fighting power of the Germans diminished by their huge expenditure of war material, nor the strategic bomber offensives of the Allies. They conducted a stubborn, often brilliant defensive strategy for two-and-a-half years, and even at the end, industrial production was still rising. The principal logistic legacy of World War II was the expertise in supplying far-off operations and a sound lesson in what is, and what is not, administratively possible.

During World War II, America won control of the Atlantic and Pacific oceans from the German and Japanese navies, and used its vast wartime manufacturing base to produce, in 1944, about 50 ships, 10 tanks, and 5 trained soldiers for every one ship, tank, and soldier the Axis powers put out. German soldiers captured by Americans in North Africa expressed surprise at the enormous stockpiles of food, clothing, arms, tools, and medicine their captors had managed to bring over an ocean to Africa in just a few months. Their own army, though much closer to Germany than the American army was to America, had chronic shortages of all vital military inventory, and often relied on captured materiel.

Across the world, America's wartime ally, the Soviet Union, was also outproducing Germany every single year. Access to petroleum was important—while America, Britain, and the Soviet Union had safe and ready access to sources of petroleum, Germany and Japan obtained their own from territories they had conquered or pressed into alliance, and this greatly hurt the Axis powers when these territories were attacked by the Allies later in the war. The 1941 Soviet decision to physically move their manufacturing capacity east of the Ural mountains and far from the battlefront took the heart of their logistical support out of the reach of German aircraft and tanks, while the Germans struggled all through the war with having to convert Soviet railroads to a gauge their own trains could roll on, and with protecting the vital converted railroads, which carried the bulk of the supplies German soldiers in Russia needed, from Soviet irregulars and bombing attacks.

1.3.6 The Korean War

The Korean War fought between the U.S.-led coalition forces against the communists offered several lessons on the importance of logistics. When the North Korean Army invaded South Korea on June 25, 1950, South Korea, including the United States, was caught by surprise. Although there were signs of an impending North Korean military move, these were discounted as the prevailing belief was that North Korea would continue to employ guerrilla warfare rather than military forces.

Compared to the seven well-trained and well-equipped North Korea divisions, the Republic of Korea (ROK) armed forces were not in a good state to repel the invasion. The U.S. 8th Army, stationed as occupation troops in Japan, was subsequently given permission to be deployed in South Korea together with the naval and air forces already there, covering the evacuation of Americans from Seoul and Inchon. The U.S. troops were later joined by the UN troops and the forces put under U.S. command.

In the initial phase of the war, the four divisions forming the U.S. 8th Army were not in a state of full combat readiness. Logistics was also in a bad shape: for example, out of the 226 recoilless rifles in the U.S. 8th Army establishment, only 21 were available. Of the 18,000 jeeps and 4×4 trucks, 55% were unserviceable. In addition, only 32% of the 13,800 6×6 trucks available were functional.

In the area of supplies, the stock at hand was only sufficient to sustain troops in peacetime activities for about 60 days. Although materiel support from deactivated units was available, they were mostly unserviceable. The lack of preparedness of the American troops was due to the assumptions made by the military planners that after 1945 that the next war would be a repeat of World War II. However, thanks to the availability of immense air and sea transport resources to move large quantities of supplies, they recovered quickly.

As the war stretched on and the lines of communication extended, the ability to supply the frontline troops became more crucial. By August 4, 1950, the U.S. 8th Army and the ROK Army were behind the Nakton River, having established the Pusan perimeter. While there were several attempts by the North Koreans to break through the defense line, the line held. Stopping the North Koreans was a major milestone in the war. By holding on to the Pusan perimeter, the U.S. Army was able to recuperate, consolidate, and grow stronger.

This was achieved with ample logistics supplies received by the U.S. Army through the port at Pusan. The successful logistics operation played a key role in allowing the U.S. Army to consolidate, grow, and carry on with the subsequent counteroffensive. Between July 2, 1950 and July 13, 1950 a daily average of 10,666 tons of supplies and equipment were shipped and unloaded at Pusan.

The Korean War highlights the need to maintain a high level of logistics readiness at all times. Although the U.S. 8th Army was able to recover swiftly thanks to the availability of vast U.S. resources, the same cannot be said for other smaller armies. On hindsight, if the U.S. 8th Army had been properly trained and logistically supported, they would have been able to hold and even defeat the invading North Koreans in the opening phase of the war. The war also indicates the power and flexibility of having good logistics support as well as the pitfalls and constraints due to their shortage.

1.3.7 Vietnam

In the world of logistics, there are few brand names to match that of the Ho Chi Minh Trail, the secret, shifting, piecemeal network of jungle roadways that helped the North win the Vietnam War.

Without this well-thought-out and powerful logistics network, regular North Vietnamese forces would have been almost eliminated from South Vietnam by the American Army within one or two years of American intervention. The Ho Chi Minh Trail enabled communist troops to travel from North Vietnam to areas close to Saigon. It has been estimated that the North Vietnamese troops received 60 tons of aid per day from this route. Most of this was carried by porters. Occasionally bicycles and horses would also be used.

In the early days of the war it took six months to travel from North Vietnam to Saigon on the Ho Chi Minh Trail. But the more people who traveled along the route the easier it became. By 1970, fit and experienced soldiers could make the journey in six weeks. At regular intervals along the route, the North Vietnamese troops built base camps. As well as providing a place for them to rest, the base camps provided medical treatment for those who had been injured or had fallen ill on the journey.

From the air the Ho Chi Minh Trail was impossible to be identified and although the United States Air Force tried to destroy this vital supply line by heavy bombing, they were unable to stop the constant flow of men and logistical supplies.

The North Vietnamese also used the Ho Chi Minh Trail to send soldiers to the south. At times, as many as 20,000 soldiers a month came from Hanoi through this way. In an attempt to stop this traffic, it was suggested that a barrier of barbed wire and minefields called the McNamara Line should be built. This plan was abandoned in 1967 after repeated attacks by the North Vietnamese on those involved in constructing this barrier.

The miracle of the Ho Chi Minh Trail "logistics highway" was that it enabled the "impossible" to be accomplished. A military victory is not determined by how many nuclear weapons can be built, but by how much necessary materiel can be manufactured and delivered to the battlefront. The Ho Chi Minh Trail enabled the steady, and almost uninterrupted, flow of logistics supplies to be moved to where it was needed to ultimately defeat the enemy.

1.3.8 Today

Immediately after World War II, the United States provided considerable assistance to Japan. In the event, the Japanese have become world leaders in management philosophies that has brought about the greatest efficiency in production and service. From organizations such as Toyota came the then revolutionary philosophies of Just in Time (JIT) and Total Quality Management (TQM). From these philosophies have arisen and developed the competitive strategies that world class organizations now practice. Aspects of these that are now considered normal approaches to management include kaizen (or continuous improvement), improved customer–supplier relationships, supplier management, vendor managed inventory, collaborative relationships between multiple trading partners, and above all recognition that there is a supply chain along which all efforts can be optimized to enable effective delivery of the required goods and services. This means a move away from emphasizing functional performance and a consideration of the whole supply chain as a total process. It means a move away from the silo mentality to thinking and managing outside the functional box. In both commercial and academic senses the recognition that supply chain management is an enabler of competitive advantage is increasingly accepted. This has resulted in key elements being seen as best practice in their own right, and includes value for money, partnering, strategic procurement policies, integrated supply chain/network management, total cost of ownership, business process reengineering, and outsourcing.

The total process view of the supply chain necessary to support commercial business is now being adopted by, and adapted within, the military environment. Hence, initiatives such as "Lean Logistics" and "Focused Logistics" as developed the U.S. Department of Defense recognize the importance of logistics within a "cradle-to-grave" perspective. This means relying less on the total integral stockholding and transportation systems, and increasing the extent to which logistics support to military operations is outsourced to civilian contractors—as it was in the 18th century. From ancient days to modern times, tactics and strategies have received the most attention from amateurs, but wars have been won by logistics.

1.4 Emergence of Logistics as a Science

In 1954, Paul Converse, a leading business and educational authority, pointed out the need for academicians and practitioners to examine the physical distribution side of marketing. In 1962, Peter Drucker indicated that distribution was the "last frontier" and was akin to the "dark continent" (i.e., it was an area that was virtually unexplored and, hence, unknown). These and other individuals were early advocates of logistics being recognized as a science. For the purpose of this section we define the science of logistics as, the study of the physical movement of product and services through the supply chain, supported by a body of observed facts and demonstrated measurements systematically documented and reported in recognized academic journals and publications.

In the years following the comments of Converse and Drucker, those involved in logistics worked hard to enlighten the world regarding the importance of this field. At the end of the twentieth century, the science of logistics was firmly in place. Works by Porter and others were major contributors in elevating the value of logistics in strategic planning and strategic management. Other well-known writers, such as Heskett, Shapiro, and Sharman, also helped elevate the importance of logistics through their writings in the most widely read and respected business publications. Because these pioneers were, for the most part, outsiders (i.e., not logistics practitioners) they were better able to view logistics from a strategic and unbiased perspective.

The emergence of logistics as a science has been steady and at times even spectacular. Before the advent of transportation deregulation in the 1980s, particularly in the 1960s and 1970s, "traffic managers" and then "distribution managers" had the primary responsibility for moving finished goods from warehouses to customers on behalf of their companies. Little, if any, attention was given to managing the inbound flows. Though many of these managers no doubt had the capacity to add significant value to their organization, their contribution was constrained by the strict regulatory environment in which they operated. That environment only served to intensify a silo mentality that prevailed within many traffic, and other logistics related, departments.

The advent of transport deregulation in the 1980s complemented, and in many cases accelerated, a parallel trend taking place—the emergence of logistics as a recognized science. The rationale behind this was that transportation and distribution could no longer work in isolation of those other functional areas involved in the flow of goods to market. They needed to work more closely with other departments such as purchasing, production planning, materials management, and customer service as well as supporting functions such as information systems and logistics engineering. The goal of logistics management, a goal that to this day still eludes many organizations, was to integrate these related activities in a way that would add value to the customer and profit to the bottom line.

In the 1990s, many leading companies sought to extend this integration end-to-end within the organization—that is, from the acquisition of raw materials to delivery to the end customer. Technology would be a great enabler in this effort, particularly the enterprise resource planning (ERP) systems and supply chain planning and execution systems that connect the internal supply chain processes. The more ambitious of the leaders sought to extend the connectivity outward to their trading partners both upstream and downstream. They began to leverage Internet-enabled solutions that allowed them to extend connectivity and provide comprehensive visibility over product flow.

As we turned the corner into the 21st century, the rapid evolution of business practices has changed the nature and scope of the job. Logistics professionals today are interacting and collaborating in new ways within their functional area, with other parts of the organization, and with extended partners. As the traditional roles and responsibilities change, the science of logistics is also changing. Logistics contributions in the future will be measured within the context of the broader supply chain.

1.5 Case Study: The Gulf War

1.5.1 Background

The Gulf War was undoubtedly one of the largest military campaigns seen in recent history. The unprecedented scale and complexity of the war presented logisticians with a formidable logistics challenge.

On July 17, 1990, Saddam Hussein accused Kuwait and the United Arab Emirates of overproduction of oil, thereby flooding the world market and decreasing its income from its sole export. Talks between Iraq and Kuwait collapsed on August 1, 1990. On August 2, Iraq, with a population of 21 million, invaded its little neighbor Kuwait, which had a population of less than two million. A few days later, Iraqi troops massed along the Saudi Arabian border in position for attack. Saudi Arabia asked the United States for help. In response, severe economic sanctions were implemented, countless United Nations resolutions passed, and numerous diplomatic measures initiated. In spite of these efforts Iraq refused to withdraw from Kuwait. On January 16, 1991, the day after the United Nations deadline for Iraqi withdrawal from Kuwait expired, the air campaign against Iraq was launched. The combat phase of the Gulf War had started.

There were three phases in the Gulf War worthy of discussion: deployment (Operation Desert Shield); combat (Operation Desert Storm); and redeployment (Operation Desert Farewell). Logistics played a significant role throughout all three phases.

1.5.1.1 Operation Desert Shield

The Coalition's challenge was to quickly rush enough troops and equipment into the theater to deter and resist the anticipated Iraqi attack against Saudi Arabia. The logistical system was straining to quickly receive and settle the forces pouring in at an hourly rate. This build-up phase, Operation Desert Shield, lasted six months. Why the six-month delay? A large part of the answer is supply.

Every general knows that tactics and logistics are intertwined in planning a military campaign. Hannibal used elephants to carry his supplies across the Alps during his invasion of the Roman Empire. George Washington's colonial militias had only nine rounds of gunpowder per man at the start of the

Revolution, but American privateers brought in two million pounds of gunpowder and saltpeter in just one year. Dwight Eisenhower's plans for the June 1944 invasion of Normandy hinged on a massive buildup of war materiel in England. The most brilliant tactics are doomed without the ability to get the necessary manpower and supplies in the right place at the right time.

During the six-month build up to the Gulf War, the United States moved more tonnage of supplies—including 1.8 million tons of cargo, 126,000 vehicles, and 350,000 tons of ordnance—over a greater distance than during the two-year build up to the Normandy invasions in World War II.

Besides the massive amount of supplies and military hardware, the logistics personnel also had to deal with basic issues such as sanitation, transport, and accommodation. A number of these requirements were resolved by local outsourcing. For example, Bedouin tents were bought and put up by contracted locals to house the troops; and refrigerated trucks were hired to provide cold drinks to the troops.

Despite the short timeframe given for preparation, the resourceful logistics team was up to the given tasks. The effective logistics support demonstrated in Operation Desert Shield allowed the quick deployment of the troops in the initial phase of the operation. It also provided the troops a positive start before the commencement of the offensive operation.

1.5.1.2 Operation Desert Storm

It began on January 16, 1991 when the U.S. planes bombed targets in Kuwait and Iraq. The month of intensive bombing that followed badly crippled the Iraqi command and control systems. Coalition forces took full advantage of this and on February 24, 1991 the ground campaign was kicked off with a thrust into the heart of the Iraqi forces in central Kuwait. The plan involved a wide flanking maneuver around the right side of the Iraqi line of battle while more mobile units encircled the enemy on the left, effectively cutting lines of supply and avenues of retreat. These initial attacks quickly rolled over Iraqi positions and on February 25, 1991 were followed up with support from various infantry and armored Divisions.

To the logisticians, this maneuver posed another huge challenge. To support such a maneuver, two Army Corps worth of personnel and equipment had to be transported westward and northward to their respective jumping off points for the assault. Nearly 4000 heavy vehicles were used. The amount of coordination, transport means, and hence the movement control required within the theater, was enormous.

One reason Iraq's army was routed in just 100 hours, with few U.S. casualties, was that American forces had the supplies they needed, where they needed them, when they needed them, and in the necessary quantities.

1.5.1.3 Operation Desert Farewell

It was recognized that the logistical requirements to support the initial build up phase and the subsequent air and land offensive operations were difficult tasks to achieve. However, the sheer scope of overall redeployment task at the end of the war was beyond easy comprehension. To illustrate, the King Khalid Military City (KKMC) main depot was probably the largest collection of military equipment ever assembled in one place. A Blackhawk helicopter flying around the perimeter of the depot would take over an hour. While the fighting troops were heading home, the logisticians, who were among the first to arrive at the start of the war, were again entrusted with a less glamorous but important "clean up job." Despite the massive amount of supplies and hardware to be shipped back, the logisticians who remained behind completed the redeployment almost six months ahead of schedule.

Throughout the war, the Commanding General, Norman Schwarzkopf, had accorded great importance to logistics. Major General William G. (Gus) Pagonis was appointed as the Deputy Commanding General for logistics and subsequently given a promotion to a three-star general during the war. This promotion symbolized the importance of a single and authoritative logistical point of contact in the Gulf War. Under the able leadership of General Pagonis, the efficient and effective logistical support system set up in the Gulf War, from deployment phase to the pull-out phase, enabled the U.S.-led coalition forces to achieve a swift and decisive victory over the Iraqi.

Both at his famous press conferences as well as later in his memoirs, Stormin' Norman called Desert Storm a "logistician's war," handing much of the credit for the Coalition's lightning-swift victory to his chief logistician, General Gus Pagonis. Pagonis, Schwarzkopf declared, was an "Einstein who could make anything happen," and, in the Gulf War, did. Likewise, media pundits from NBC's John Chancellor on down also attributed the successful result of the war to logistics.

1.5.2 Lessons Learned from the Gulf War

1.5.2.1 "Precision Guided" Logistics

In early attempts inside and outside of the Pentagon to assess the lessons learned from the Gulf War, attention has turned to such areas as the demonstrated quality of the joint operations, the extraordinary caliber of the fighting men and women, the incredible efficacy of heavy armor, the impact of Special Forces as part of joint operations on the battlefield, and the success of precision-guided weapons of all kinds. Predictably lost in the buzz over celebrating such successes was the emergence and near-seamless execution of what some have termed "precision-guided" logistics.

Perhaps, this is as it should be. Logistics in war, when truly working, should be transparent to those fighting. Logistics is not glamorous, but it is critical to military success. Logisticians and commanders need to know "what is where" as well as what is on the way and when they will have it. Such visibility, across the military services, should be given in military operations.

1.5.2.2 "Brute Force" Logistics

In 1991, the United States did not have the tools or the procedures to make it efficient. The Gulf War was really the epitome of "brute force" logistics. The notion of having asset visibility—in transit, from factory to foxhole—was a dream. During the Gulf War, the Unites States did not have reliable information on almost anything. Materiel would enter the logistics pipeline based on fuzzy requirements, and then it could not be readily tracked in the system.

There were situations where supply sergeants up front were really working without a logistics plan to back up the war plan. They lacked the necessary priority flows to understand where and when things were moving. It was all done on the fly, on a daily basis, and the U.S. Central Command would decide, given the lift they had, what the priorities were. Although progress was eventually made, often whatever got into the aircraft first was what was loaded and shipped to the theater. It truly was brute force.

Even when air shipments were prioritized there was still no visibility. Although it is difficult to grasp today, consider a load being shipped and then a floppy disk mailed to the receiving unit in the theater. Whether that floppy disk got where it was going before the ship got there was in question. Ships were arriving without the recipients in the theater knowing what was on them.

Generally speaking, if front-line commanders were not sure of what they had or when it would get there, they ordered more. There were not enough people to handle this flow, and, in the end, far more materiel was sent to the theater than was needed. This was definitely an example of "just-in-case" logistics. When the war ended, the logistics pipeline was so highly spiked that there were still 101 munitions ships on the high seas. Again, it was brute-force logistics.

The result was the off-referenced "iron mountains" of shipping containers. There was too much, and, worse yet, little, if any, knowledge of what was where. This led, inevitably, to being forced to open something like two-thirds of all of the containers simply to see what was inside. Imagine the difficulty in finding things if you shipped your household goods to your new house using identical unmarked boxes. Since there were a great number of individual users, imagine that the household goods of all of your neighbors also were arriving at your new address, and in the same identical boxes.

That there was this brute force dilemma in the Gulf War was no secret. There just wasn't any other way around it. The technology used was the best available. Desert Storm was conducted using 286-processor technology with very slow transfer rates, without the Internet, without the Web, and without encrypted satellite information. Telexes and faxes represented the available communication technology.

1.5.2.3 "Flying Blind" Logistics

This was an era of green computer screens, when it took 18 keystrokes just to get to the main screen. When the right screen was brought up, the data were missing or highly suspect (i.e., "not actionable"). In contrast to today, there were no data coming in from networked databases, and there was no software to reconcile things. There were also no radio frequency identification tags. In effect, this was like "flying blind."

In fact, nothing shipped was tagged. Every shipment basically had a Government bill of lading attached to it, or there were five or six different items that together had one bill of lading. When those items inevitably got separated, the materiel was essentially lost from the system. Faced with this logistics nightmare, and knowing that there was often a critical need to get particular things to a particular place at a particular time, workarounds were developed.

As a result of our experience in the Gulf War, the Department of Defense (DOD) has subsequently been refining its technologies and testing them through military joint exercises and deployments and contingencies in such places as Bosnia, Kosovo, and Rwanda. Specifically, the DOD has focused on the issue of logistics management and tracking and on how technology can enable improvements in this mission critical area. The DOD has improved its logistics management and tracking through policy directives and by engaging with innovative technology companies in the development and leveraging of technical solutions.

The DOD now has clear knowledge of when things are actually moving—the planes, the ships, what is going to be on them, and what needs to be moved. Communication is now digital and that represents a quantum leap in capability and efficiency from the first war in Iraq. Operators now get accurate information, instantaneously, and where needed. The technology exists to absorb, manage, and precisely guide materiel.

1.5.3 Applying Lessons Learned from the Gulf War

1.5.3.1 Operation Enduring Freedom

While troops raced toward Baghdad in the spring of 2003, digital maps hanging from a wall inside the Joint Mobility Operations Center at Scott Air Force Base, Ill, blinked updates every four minutes to show the path cargo planes and ships were taking to the Middle East. During the height of the war in Iraq, every one of the military's 450 daily cargo flights and more than 120 cargo ships at sea were tracked on the screen, as was everything stowed aboard them—from Joint Direct Attack Munitions to meals for soldiers.

In rows of cubicles beneath the digital displays, dozens of military and civilian workers from the U.S. Transportation Command (TRANSCOM) looked at the same maps on their computer screens. The maps, along with an extensive database with details on more than five million items and troops in transit, came in handy as telephone calls and e-mail queries poured in from logisticians at ports and airfields in the Persian Gulf: How soon would a spare part arrive? When would the next shipment of meals arrive? When was the next batch of troops due? With just a few mouse clicks, TRANSCOM workers not only could report where a ship or plane was and when it was due to arrive, but also could determine which pallet or shipping container carried what. In many cases, logisticians in the field also could go online, pull up the map and data and answer their own questions.

Vice Admiral Keith Lippert, director of the Defense Logistics Agency (DLA) says the war in Iraq validated a new business model that moves away from "stuffing items in warehouses" to relying on technology and contractors to provide inventory as needed. The agency, which operates separately from TRANSCOM, is responsible for ordering, stocking, and shipping supplies shared across the services. In addition, the Army, Navy, Air Force, and Marines have their own supply operations to ship items unique to each service. The DLA supplied several billion dollars worth of spare parts, pharmaceuticals, clothing and 72 million ready-to-eat meals to troops during the war.

Military logisticians have won high marks for quickly assembling the forces and supplies needed in Iraq. Advances in logistics tracking technology, investments in a new fleet of cargo airplanes and larger ships, and the prepositioning of military equipment in the region allowed troops to move halfway around the world with unprecedented speed. Troops were not digging through containers looking for supplies they had ordered weeks earlier, nor were they placing double and triple orders in hopes that one of their requests would be acted upon, as they did during the Gulf War in 1991. While the military transportation and distribution system may never be as fast or efficient as FedEx or UPS, its reliability has increased over the past decade.

Nonetheless, challenges remain. Several changes to the way troops and supplies are sent to war are under consideration, including:

- Further improvement of logistics information technology systems
- Development of a faster way to plan troop deployments
- Consolidated management of the Defense supply chain

While TRANSCOM has gotten positive reviews for moving troops and supplies to the Middle East, concerns have been raised about how the services moved supplies after they arrived in the field.

Perhaps the most valuable logistics investment during the war was not in expensive cargo aircraft or advanced tracking systems, but in thousands of plastic radio frequency identification labels that cost $150 apiece. The tags, which measure eight inches long by about two inches wide, contain memory chips full of information about when a shipment departed, when it is scheduled to arrive and what it contains. They are equipped with small radio transponders that broadcast information about the cargo's status as it moves around the world. The tags enable the Global Transportation Network to almost immediately update logistics planners on the location of items in the supply chain.

These tags were a key factor in avoiding the equipment pileups in warehouses and at desert outposts that came to symbolize logistics failings during the first Gulf War. The tags also saved hundreds of millions of dollars in shipping costs, logisticians say. For example, British soldiers spent almost a full day of the war searching cargo containers for $3 million in gear needed to repair vehicles. Just as they were about to place a second order for the gear, a U.S. logistician tapped into a logistics tracking system and was able to locate the supplies in the American supply network.

Rapid response to shifting requirements is clearly the fundamental challenge facing all logisticians, as relevant in the commercial sector as it is in the military environment. The commercial logistician requires the same thing that the combatant commander requires: situational awareness. We all need an in-depth, real-time knowledge of the location and disposition of assets.

Indeed, Wal-Mart, arguably the channel master for the world's largest, most globally integrated commercial supply chain, has embarked on a passive RFID initiative that is very similar to the Department of Defense's plans. The retailer mandated that suppliers tag inbound materiel with passive RFID tags beginning at the case and pallet level. Wal-Mart established a self-imposed January 2005 deadline to RFID-enable its North Texas operation, along with 100 of its suppliers. The first full-scale operational test began on April 30, 2005. Based on the success of this initial test Wal-Mart expanded its supplier scope and deployment plan for RFID and by early 2007 reported that some 600 suppliers were RFID-enabled.

While there have been some solid successes early on, there are now many suppliers (in particular the smaller ones) that are dragging their feet on RFID adoption due to an elusive return on investment (ROI). Current generation RFID tags cost about 15 cents, while bar codes cost a fraction of a cent. Suppliers have also had to absorb the cost of buying hardware—readers, transponders, antennas—and software to track and analyze the data. The tags also have increased labor. Bar codes are printed on cases at the factory, but because most manufacturers have yet to adopt RFID, tags have to be put on by hand at the warehouse. The retail giant also experienced difficulties rolling out RFID in their distribution network. Wal-Mart had hoped to have up to 12 of its roughly 137 distribution centers using RFID technology by the end of 2006, but had installed the technology at just five. Now Wal-Mart has shifted gears from their distribution centers to their stores where they believe they will be better able to drive sales for their suppliers and to get product on the shelf, where it needs to be for their customers to buy. By early 2007 there were roughly 1000 stores RFID-enabled with another 400 stores planned by the end of the year.

Regardless of where Wal-Mart places their priorities, with this retail giant leading the charge, and driving industry compliance, it is expected that this initiative will have a greater, and more far-reaching, impact on just the retail supply chain. Virtually every industry, in every corner of the planet, will be fundamentally impacted sometime in the not-too-distant future. Clearly the lessons learned in military logistics are being applied to business logistics and as a result engineering logistics.

2

Economic Impact of Logistics

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2.1 Expenditures in the United States and Worldwide

As the world continues to develop into a homogenized global marketplace the growth in world merchandise trade has outpaced the growth in both global production and the worldwide economy. In 2006, world merchandise trade increased 8%, while the global economy rose only 3.7%.* Globalization has dramatically shifted where logistics dollars are spent as developing countries now account for over one-third of world merchandise exports. Increased world trade means higher demand for logistics services to deliver the goods. Expenditures for logistics worldwide are estimated at well over $4 trillion in 2006 and now account for about 15% to 20% of finished goods cost.† Growth in world merchandise trade, measured as export volume, has exceeded the growth in the worldwide economy, as measured by Gross Domestic Product (GDP), for close to two decades. Although the worldwide economy slowed to some extent in late 2006 and early 2007, trade volumes are predicted to continue to rise well into the next decade.

This phenomenal growth in world trade has profound implications for logistics. In the past five years the demand for shipping has outstripped the capacity in many markets, altering the supply demand equilibrium and pushing up prices. It now costs from 15% to 20% more to move products than it did in 2002. Shifts in global manufacturing as the United States continues to move manufacturing facilities to other global markets with lower labor costs, such as China, India, and South Korea, are redrawing the landscape for transportation strategies. The growth was led by Asia and the so-called transition economies (Central and Eastern Europe and the Russian Trade Federation). In real terms these regions experienced 10–12% growth rates in merchandise exports and imports. China, for instance, has seen the most dramatic trade growth, with a 27% jump in 2006. The World Trade Organization (WTO) recently

* World Trade Organization Press Release, "World Trade 2006, Prospects for 2007," April 12, 2007.

† Estimated from a 2003 figure for global logistics of $3.43 trillion. Report from the Ad Hoc Expert Meeting on Logistics Services by the United Nations Conference on Trade and Development's (UNCTAD) Trade and Development Board, Commission on Trade in Goods and Services, and Commodities, Geneva, July 13, 2006.

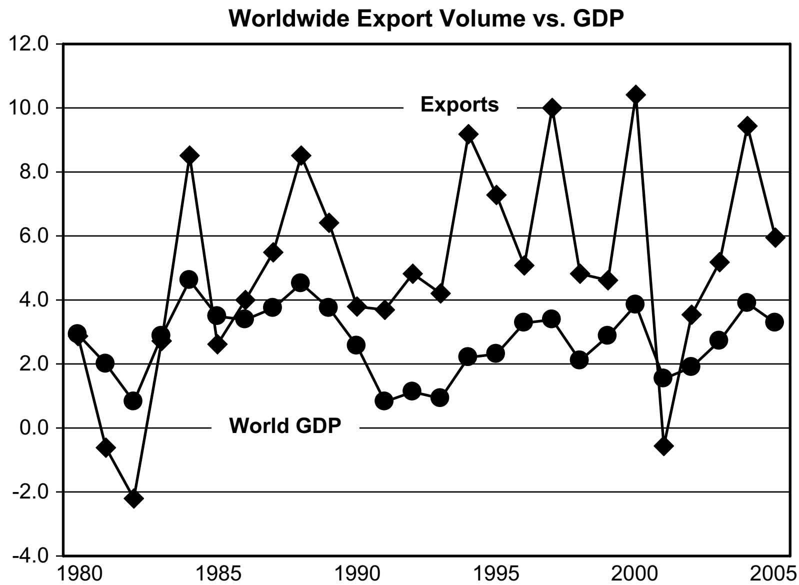

FIGURE 2.1 Worldwide export volume vs. GDP. (From World Trade Organization, International Trade Statistics, 2006.)

reported that China's merchandise exports actually exceeded those of the United States, the market leader, for the second half of 2006. Worldwide export volumes as a percentage of world GDP appear in Figure 2.1.

Studies have shown that total expenditures as a percentage of GDP are generally lower in more efficient industrialized countries, usually 10% or less. Conversely less-developed countries expend a much greater portion of their GDP, 10–20%, on logistics. Where a country falls on the spectrum depends on factors such as the size and disbursement of the population, the level of import and export activity, and the type and amount of infrastructure development. The relative weights for the components of total logistic costs vary significantly by country, with carrying costs accounting for 15–30%, transportation expenditures for another 60–80%, and administrative costs for the remaining 5–10%. Logistics cost in the United States have been holding steady at just under 10% of GDP. The breakout for the components of U.S. logistics costs are 33% for carrying costs, 62% for transportation costs, and about 4% for administrative costs. Additional detail is provided in Figure 2.2.

During 2005, the cost of the U.S. business logistics system increased to $1.18 trillion, or the equivalent of 9.5% of nominal GDP. Logistics costs have gone up over 50% during the last decade. The year 2005 was a year of record highs for many of the components of the model, especially transportation costs, mostly trucking. Transportation costs jumped 14.1% over 2004 levels, and 77.1% during the past decade. Yet, total logistics costs remained below 10% of GDP.

2.2 Breakdown of Expenditures by Category

The cost to move goods encompasses a vast array of activities including supply and demand planning, materials handling, order fulfillment, management of transportation and third-party logistics (3PLs) providers, fleet management, and inventory warehouse management. To simplify, logistics can be defined as the management of inventory in motion or at rest. Transportation costs are those incurred when the inventory is in motion, and inventory carrying costs are those from inventory at rest awaiting

2005 U.S. Business Logistics System Cost

				$ Billions
Carrying Costs - $1.763 Trillion All Business Inventory				
Interest				58
Taxes, Obsolescence, Depreciation, Insurance				245
Warehousing				90
			Subtotal	393
Transportation Costs				
Motor Carriers:				
Truck - Intercity				394
Truck - Local				189
			Subtotal	583
Other Carriers:				
Railroads				48
Water	I 29	D 5		34
Oil Pipelines				9
Air	I 15	D 25		40
Forwarders				22
			Subtotal	153
Shipper Related Costs				8
Logistics Administration				46
	TOTAL LOGISTICS COST			1183

FIGURE 2.2 Breakdown of U.S. business logistics system costs. (From 17th Annual State of Logistics Report, Rosalyn Wilson, CSCMP, 2006.)

the production process or in storage awaiting consumption. The third broad category of logistics cost is administrative costs, which encompass the other costs of carrying out business logistics that is not directly attributable to the first two categories. The cost of the U.S. business logistics system as measured by these three categories was $1183 billion in 2005.*

2.2.1 Carrying Costs

Carrying costs are the expenses associated with holding goods in storage, whether that be in a warehouse or, as is increasingly done today, in a shipping container, trailer, or railcar. There are three subcomponents that comprise carrying cost. The first is interest and that represents the opportunity cost of money invested in holding inventory. This expense will vary greatly depending on the level of inventory held and the interest rate used. The second subcomponent covers inventory risk costs and inventory service costs and comprises about 62% of carrying cost expense. These are measured by using expenses for obsolescence, depreciation, taxes, and insurance. Obsolescence includes damages to inventory and shrinkage or pilferage, as well as losses from inventory which cannot be sold at value because it was not moved through the system fast enough. In today's fast paced economy with quick inventory turns, obsolescence represents a significant cost to inventory managers. The taxes are the *ad valorem* taxes collected

* Logistics expenditures for the United States have been measured consistently and continuously for the "Annual State of Logistics Report" developed by Robert V. Delaney of Cass Logistics in the mid-1980s and continued today by Rosalyn Wilson. The methodology used by Mr. Delaney was based on a model developed by Nicholas A. Glaskowsky, Jr., James L. Heskett, Robert M. Ivie in *Business Logistics*, 2nd edition, New York, Ronald Press, 1973. The Council for Supply Chain Management Professionals (CSCMP) has sponsored the report since 2004.

on inventory and will vary with inventory levels. Insurance costs are the premiums paid to protect inventory and mitigate losses. The final subcomponent is warehousing. Warehousing is the cost of storing goods and has traditionally included both public and private warehouses, including those in manufacturing plants. The market today includes a wide variety of storage possibilities from large mega-distribution centers, to smaller leased facilities, to container and trailer-storage yards.

In 2005, inventory carrying costs rose 17%—the highest level since 1971. The increase was due to both significantly higher interest rates than in 2004 and a rise in inventories. The average investment in all business inventories was $1.74 trillion, which surpassed 2004's record high by $101 billion. Both the inventory-to-sales ratio and the inventory-to-factory shipments ratio have been rising steadily in recent years. Inventories have been slowly creeping up since 2000, reversing the trend to leaner inventories from the previous decade. The globalization of production has driven the economy away from the lean just-in-time inventory management model of the 1990s. Stocks are increasingly maintained at a higher level in response to longer and sometimes unpredictable delivery times, as well as changes in distribution patterns. Manufacturers and retailers have struggled to achieve optimum inventory levels as they refine their supply chains to mitigate uncertain delivery times, add new sources of supply, and become more adept at shifting existing inventories to where they are most advantageous. On an annualized basis, the value of all business inventory has risen every year since 2001, as depicted graphically in Figure 2.3.

2.2.2 Transportation Costs

Transportation costs are the expenditures to move goods in various states of production. This could include the movement of raw materials to manufacturing facilities, movement of components to be included in the final product, to the movement of final goods to market. Transportation costs are measured by carriers' revenues collected for providing freight services. All modes of transportation are included: trucking, intercity and local; freight rail; water, international and domestic; oil pipeline; both international and domestic airfreight transport; and freight forwarding costs, not included in carrier

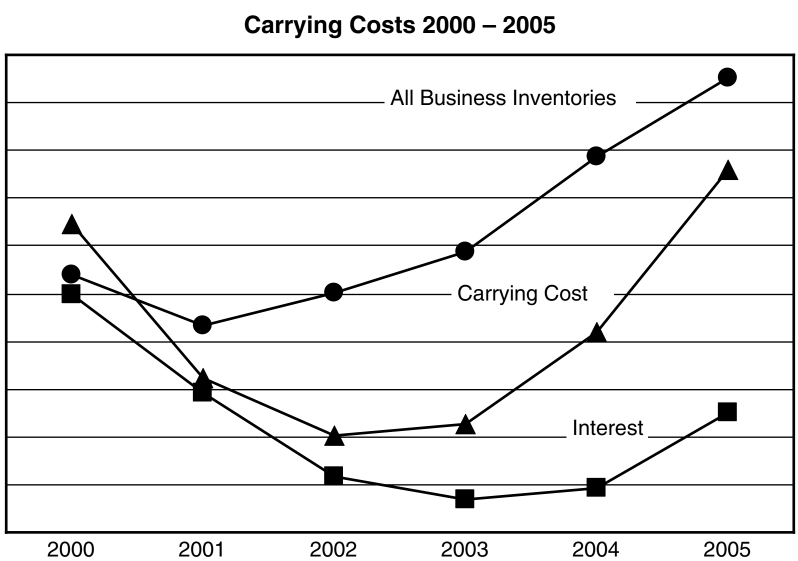

FIGURE 2.3 Costs associated with inventories. (From 17th Annual State of Logistics Report, Rosalyn Wilson, CSCMP, 2006.)

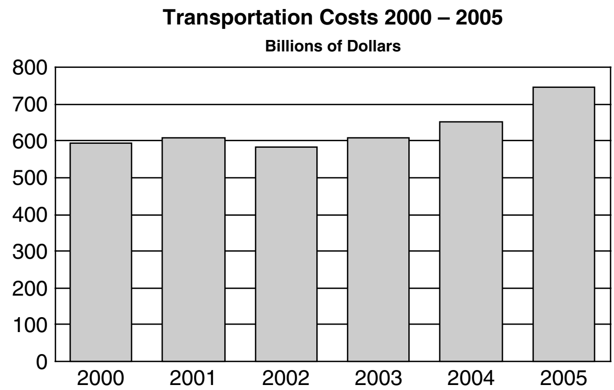

FIGURE 2.4 Transportation costs. (From 17th Annual State of Logistics Report, Rosalyn Wilson, CSCMP, 2006.)

revenue. Transportation includes movement of goods by both public and private, or company-owned, carriers. The freight forwarder expenditures are for other value-added services provided by outside providers exclusive of actual transportation revenue which is included in the modal numbers. Transportation costs are the single largest contributor to total logistics costs, with trucking being the most significant subcomponent. Figure 2.4 shows recent values for these costs.

Trucking costs account for roughly 50% of total logistics expenditures and 80% of the transportation component. Truck revenues are up 21% since 2000, but that does not tell the whole story. In 2002, trucking revenues declined for the first time since the 1974–1975 recession. During this period demand was soft and rates were dropping, fuel prices were soaring, insurance rates were skyrocketing. The trucking industry was forced to undergo a dramatic reconfiguration. About 10,000 motor carriers went bankrupt between 2000 and 2002, and many more were shedding their terminal and other real estate and non-core business units to survive.* While the major impact was the elimination of many smaller companies with revenues in the $5–$20 million range, there were some notable large carriers including Consolidated Freightways. Increased demand and tight capacity enabled trucking to rebound in 2003 and it has risen steadily since.

Trucking revenues in 2005 increased by $74 billion over 2004, but carrier expenses rose faster than rates, eroding some of the gain. The hours-of-service rules for drivers have had a slightly negative impact by reducing the "capacity" of an individual driver, at the same time a critical driver shortage is further straining capacity. The American Trucking Association (ATA) has estimated that the driver shortage will grow to 111,000 by 2014. Fuel ranks as a top priority at trucking firms as substantially higher fuel prices have cut margins. However, for many the focus has shifted from the higher price level to the volatility of prices. The U.S. trucking industry consumes more than 650 million gallons of diesel per week, making it the second largest expense after labor. The trucking industry spent $87.7 billion for diesel in 2005, a big jump over the $65.9 billion spent in 2004.

Rail transportation has enjoyed a resurgence as it successfully put capacity and service issues behind. Freight ton-mile volumes have reached record levels for nine years in a row. Despite a growth of 33% since 2000, rail freight revenue accounts for only 6.5% of total transportation cost. Intermodal shipping has given new life to the rail industry, with rail intermodal shipments more than tripling since 1980, up from 3.1 to 9.3 million trailers and containers. Sustained higher fuel prices have made shipping by rail a more cost-effective mode than an all truck move. High demand kept the railroad industry operating at

* Donald Broughton tracks bankruptcies in a proprietary database for A.G. Edwards and Sons.

near capacity throughout 2005, bumping revenue 14.3%. The expansion of rail capacity has become a paramount issue. The Association of American Railroads (AAR) has reported that railroads will spend record amounts of private capital to add new rail lines to double and triple track existing corridors where needed. In addition, freight railroads are expected to hire 80,000 new workers by 2012.

Water transportation is comprised of two major segments—domestic and international or oceangoing. The international segment has been the fastest growing segment leaping over 60% since 2000, from $18 billion to $29 billion. This tracks with the dramatic growth in global trade. Domestic water traffic, by comparison, has actually declined 30% since 2000, falling from $8 billion to $5 billion in 2005. The United States continues to struggle with port capacity problems, both in terms of available berths for unloading and throughput constraints which slow down delivery.

Water transportation faces many obstacles to its continued health. Given the expected growth in international trade U.S. ports are rapidly becoming inadequate. Many ports are over fifty years old and are showing signs of neglect and obsolescence and many have narrow navigation channels and shallow harbors that do not permit access by deep draft vessels which are becoming predominant in the world-wide fleet. The U.S. ports system is close to reaching the saturation point. The World Shipping Council estimates that over 800 ocean freight vessels make over 22,000 calls at U.S. ports every year, or over 60 vessels a day at the nation's 145 ports. Even worse, while the U.S. has done little more than maintain our ports, ports throughout Asia and Europe have become more modern and efficient, giving them an edge in the global economy. As global trading partners build port facilities to handle the larger ships the U.S. places itself at an even greater competitive disadvantage.

The domestic waterway system, the inland waterways, and Great Lakes, has also been the victim of underinvestment. For too many years there has been a lack of resources aimed at maintaining and improving this segment of our transportation network and it is beginning to have dramatic impacts on the capacity of the system. Dredging has fallen behind and the silt built up is hampering navigation and the nation's lock systems are aged and crumbling, with 50% of them obsolete today. Revitalizing this important transportation segment and increasing its use could have a significant impact on reducing congestions and meeting demand for capacity. Although it is not very prevalent now, waterways could even handle containers. A single barge can move the same amount of cargo as 58 semi-trucks at one-tenth the cost.

The air cargo industry has both a domestic and an international side. It is primarily composed of time-sensitive shipments for which customers are willing to pay a premium. Both markets are strong with international revenue up almost 88% since 2000 and domestic revenues up 32% during the same period. Although the air cargo market is thriving and growing, it is still a relatively small share of the whole, representing only about 5% of transport costs. Airfreight revenues increased by $6 billion during 2005, which was an increase of 17.6% over 2004. Along with the growth in revenue came skyrocketing expenses, especially for fuel. In 2003, fuel represented about 14% of operating expenses and in 2005 the percentage had grown to 22%.

The next segment, oil pipeline transportation, accounts for slightly over 1% of total transportation costs. It includes the revenue for the movement of crude and refined oil. We have not added much capacity in the last decade and costs have remained stable, so revenues have been largely constant since 2000.

The final segment, forwarders, has increased over two and half times since 2000, rising from $6 billion to $22 billion. It is important to note that this segment does not include actual transportation expenses, those are picked up in the figures for each mode. Freight forwarders provide and ever increasing array of services as they adapt to meet the changing needs of shippers who chose to outsource their freight needs. The most basic function of a forwarder is to procure carrier resources and facilitate the freight movement. Globalization was a boon to such third-party providers as they specialized in the processes and documentation necessary to engage in international trade. Today forwarders offer such services as preparation of export and import documentation, consolidation and inspection services, and supply chain optimization consulting.

2.2.3 Administrative Costs

The final component of logistics cost is administrative costs and it has two subcomponents: shipper-related costs and logistics administration costs. Shipper-related costs are expenses for logistics-related functions performed by the shipper that are in addition to the actual transportation charges, such as the loading and unloading of equipment, and the operation of traffic departments. Shipper costs actually amounts to less than 1% of total logistics costs.

Logistics administration costs represent about 4% of total logistics costs. It includes corporate management and support staff who provide logistics support, such as supply chain planning and analysis staff and physical distribution staff. Computer software and hardware costs attributable to logistics are included in this category if they cannot be amortized directly elsewhere.

2.3 Logistics Productivity over the Past 25 Years

There has been a dramatic improvement in the U.S. business logistics system in the past 20 years. Inventory carrying costs as a percentage of GDP has declined about 40%. Transportation costs as a percentage of GDP dropped by 8% and total logistics costs declined by 23%. Logistics costs as a percentage of nominal GDP has been below 10% since 2000, despite a 25% increase in the last two years. Imports into the United States, as measured by TEUs, has jumped from under 50 million units to over 400 million in the past 26 years, despite the fact that the capacity growth rate of the nation's transportation infrastructure has been static.

Logistics costs in the United States, and to some extent Europe, have dropped significantly since the deregulation of the transportation modes in the 1980s. Much of the gain was due to reductions in inventory costs. The improved performance of the U.S. logistics sector can be traced to the regulatory reforms in the 1980s. All modes were substantially deregulated, including trucking, rail and air, and after a period of six to eight years of adjustment the economy began to reap the benefits of enhanced productivity, rationalized rail lines, and expanded use of rate contracts. Investments in public infrastructure, particularly the interstate highway system and airports, initially contributed to improved performance in the industry. For the last decade the United States has seriously lagged behind in the necessary investment to sustain the growth however. Much of the gain has come from private innovations and companies agile enough to change rapidly with the times. Examples are the appearance and then explosive growth of the express shipping market, just in time and lean inventory practices which are now being replaced with carefully managed inventories that can be redirected instantaneously, mega retail stores like Wal-Mart and Target with clout to influence logistics practices, and logistics outsourcing.

Over the last 15 years, there has not been a dramatic shift in the relative weights for each of the components that make up total logistics costs. Carrying costs represented 39% of total logistics costs in 1989 and account for 32% today, while transportation costs have climbed from a 56% share to a 62% share of the total. With the exception of carrying costs, each of the other components have risen over 60% since 1989, with both transportation and shipper-related costs jumping 75%. (See Fig. 2.5 for a graphical depiction of trends.)

The nation's railroads move over 50% of all international cargo entering the United States for some portion of the move. International freight is expected to double its current level by 2025. Although the railroads have made heavy investments in recent years in equipment and additional labor, average train speed is falling. Truck vehicle-miles traveled on U.S. highways have nearly doubled in the last 25 years. According to the Federal Highway Administration (FHWA), the volume of freight traffic on the U.S. road system will increase 70% by 2020. Also by 2020, the highway system will have to carry an additional 6.6 billion tons of freight—an increase of 62%. Slower trains mean higher costs and more congestion. Statistics published by the AAR show that average train speed for the entire United States declined from 23 miles per hour in 2000 to less than 22 miles per hour in 2005. The rail freight network was rationalized shortly after the passage of the Staggers Act in 1980 and is now about one-half the size it was, prior

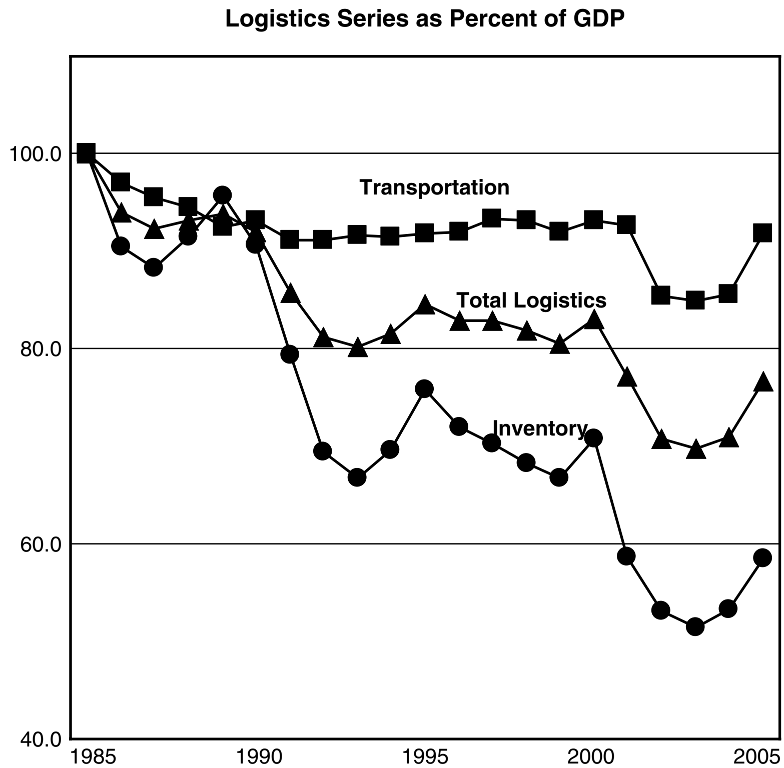

FIGURE 2.5 Logistics series as a percentage of GDP. (From 17th Annual State of Logistics Report, Rosalyn Wilson, CSCMP, 2006.)

to 1980. The leaner system is more productive however, and carries almost double the number of ton-miles the old system carried. Yet, shippers are pushing for even more efficiencies in this area. Will the old strategies applied so successfully in the past work in the rapidly changing global environment? Perhaps, the evidence will show that to maintain the gains we have made and to improve the U.S. world competitiveness will require innovation and a re-engineering of supply chain management. Leading the pack in this arena is the contract logistics market.

Market location has become one of the most important drivers of logistics cost. The push by the United States to locate manufacturing facilities offshore to take advantage of less-expensive labor and abundant resources has caused a shift in trade patterns. Logistics services that were traditionally performed largely by developed nations are now increasingly being carried out by emerging economies. Now developing countries move finished goods, in addition to raw materials.

The growth and market clout of mega-retailers like Wal-Mart increased the pressure to reduce costs and increase efficiency, forcing many companies to outsource pieces of their supply chain, often to offshore resources. However, global manufacturing is driving many companies to devise innovative strategies for ensuring reliable sources of goods. The ongoing shift of manufacturing to Asia has added stress to an already congested and overburdened domestic transportation system, particularly on shipping in the Pacific. The region has already been operating at full capacity.

Another interesting demographic is the number of small companies now participating in global trade, which had been the purview of large multinational companies until the late 1990s. Over 80% of corporations surveyed in 2002, ranging from small businesses to global giants, indicated that they operated on a global scale. Most operate distribution, sales or marketing centers outside of their home markets.

The globalization of trade and logistics operations has led to the development of international operators based in the regional hubs of developing regions, with Hong Kong, Singapore, United Arab Emirates, and the Philippines. These entities have refined their processes and often employed state-of-the-art equipment to enhance their productivity. The infrastructure has often been built from the ground up with today's global climate in mind. These companies now account for over 30% of global terminal operations.

Many U.S. shippers are contracting their logistics out to non-U.S.-based providers. The estimated value globally for contract logistics services has exceeded $325 billion, with the U.S. portion estimated to be about $150 billion. Shippers are now outsourcing one or more of their supply chain management activities to 3PLs service suppliers. These providers specialize in providing integrated logistics services that meet the needs of today's highly containerized freight system. These companies have proven to be particularly adaptable to the changing global environment including the use of larger and faster ships, containerization of freight, increased security requirements, new technologies to track and monitor shipments, and the rise in air transport for time-sensitive shipments. The global marketplace seemed to emerge overnight and most companies were not prepared or agile enough to respond to the changes. A new knowledge-based needed to be acquired and the rules were constantly changing. Third-part providers provided the answers to these problems. These companies filled the niche and became experts, enabling even the smallest firms to operate multinationally. The most successful of these companies control a major share of the market and they play a key role in our ability to expand our supply chains into international markets.

3

Logistics Engineering Tool Chest

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3.1 Introduction

Logistic systems are systems of big dimensions that are geographically dispersed in space. Their complexity is caused by many factors. Interactions between decision-makers, drivers, workers and clients; vehicles, transportation and warehousing processes; communication systems and modern computer technologies which are very complex. Logistics has been defined by the Council of Logistics Management as "... the process of planning, implementing, and controlling the efficient, effective flow and storage of goods, services, and related information from point of origin to point of consumption for the purpose of conforming to customer requirements." This definition includes inbound, outbound, internal, and external movements, and return of materials for environmental purposes.

Many aspects of logistic systems are stochastic, dynamic, and nonlinear causing logistic systems to be highly sensitive even to small perturbations. Management and control of modern logistic systems is based on many distributed, hierarchically organized levels. Decision-makers, dispatchers, drivers, workers, and clients have different interests and goals, different educational levels, and diverse work experience. They perceive situations in different ways, and make a lot of decisions based on subjective perceptions and subjectively evaluated parameters.

Management and control of modern logistic systems are based on Management Science (MS), Operations Research (OR), and Artificial Intelligence (AI) techniques. Implementation of specific control actions is possible because of a variety of classical and modern electronic, communication, and information technologies that are vital parts of logistic infrastructure. These technologies significantly contribute to the efficient distribution, lower travel times and traffic congestion, lower production and transportation costs, and higher level of service.

Observation, analysis, prediction of future development, control of complex systems, and optimization of these systems represent some of the main research tasks within OR. Analysis of system behavior assumes development of specific theoretical models capable of accurately describing various system processes. The developed mathematical models are used to predict system behavior in the future, to plan future system development, and to define various control strategies and actions. Logistic systems characterized by complex and expensive infrastructure and equipment, great number of various users, and uncertain value of many parameters, have been one of the most important and most challenging OR areas.

Artificial Intelligence is the study and research in computer programs with the ability to display "intelligent" behavior. (AI is defined as a branch of computer science that studies how to endow computers with capabilities of human intelligence.) In essence, AI tries to mimic human intelligent behavior. AI techniques represent convenient tools that can reasonably describe behavior and decision-making of various decision-makers in production, transportation, and warehousing. Distributed AI and multi-agent systems are especially convenient tools for the analysis of various logistic phenomena.

During the last decade, significant progress has been made in merging various OR and AI techniques.

3.2 Operations Research: Basic Concepts

The basic OR concepts can be better described with the help of an example. Let us consider the problem of milk distribution in one city. Different participants in milk distribution are facing various decision problems. We assume that the distributor has a fleet composed of a few vehicles. These vehicles should deliver milk and dairy products to 50 different stores. The whole distribution process could be organized in many different ways. There are number of feasible vehicle routes. The dispatcher in charge of distribution will always try to discover vehicle routes that facilitate lowest transportation costs.

Store managers are constantly facing the problem of calculating the proper quantity of milk and dairy products that should be ordered from the distributor. Unsold milk and other products significantly increase the costs. On the other hand, potential revenue could be lost in a case of shortage of products.

Both decision problems (faced by distributor dispatcher and store managers) are characterized by limited resources (the number of vehicles that can participate in the milk distribution, the amount of money that could be invested in milk products), and by the necessity to discover optimum course of action (the best set of vehicle routes, the optimal quantities of milk and dairy products to be ordered).

Operations Research could be defined as a set of scientific techniques searching for the best course of action under limited resources. The beginning of OR is related to the British Air Ministry activities in 1936, and the name Operations Research (Operational Research) has its roots in research of military operations. The real OR boom started after World War II when OR courses were established at many American Universities, together with extensive use of OR methods in industry and public sector. The development of modern computers further contributed to the success of OR techniques.

Formulation of the problem (in words) represents the first step in the usual problem solving scheme. In the next step, verbal description of the problem should be replaced by corresponding mathematical formulation. Mathematical formulation describes the problem mathematically. Variables, objective function, and constraints are the main components of the mathematical model. To build a mathematical model, analysts try to establish various logical and mathematical relationships between specific variables. The analysts define the objective function, as well as the set of constraints that must be satisfied. Depending on the problem context, the constraints could be by their nature physical, institutional, or financial resources. The generated feasible solutions are evaluated by corresponding objective function values. The set of feasible solutions is composed of all problem solutions that satisfy a given set of constraints. It is very difficult (and in majority of cases impossible) to produce mathematical model that will capture all different aspects of the problem considered. Consequently, mathematical models represent simplified description of the real problem. Practically, all mathematical models represent the compromise between the wish to accurately describe the real-life problem and the capability to solve the mathematical model.

3.2.1 Problem Solving Steps

Many real-life logistic and transportation problems can be relatively easily formulated in words (Fig. 3.1). After such formulation of the problem, in the next step, engineers usually translate problem's verbal description into a mathematical description.

Main components of the mathematical description of the problem are variables, constraints, and the objective. Variables are sometimes called *unknowns*. While some of the variables are under the control of the analyst, some are not. Constraints could be physical resources, caused by some engineering rules, laws, guidelines, or due to various financial reasons. One cannot accept more than 100 passengers for the planned flight, if the capacity of the aircraft equals 100 seats. This is a typical example of physical constraint. Financial constraints are usually related to various investment decisions. For example, one cannot invest more than \$10,000,000 in road improvement if the available budget equals \$10,000,000. Solutions could be feasible or infeasible. Solutions are feasible when they satisfy all the defined constraints. An objective represents the end result that the decision-maker wants to accomplish by selecting a specific program or action. Revenue maximization, cost minimization, or profit maximization are typical objectives of profit-oriented organizations. Providing the highest level of service to the customers represents the usual objective of a nonprofit organization.

Mathematical description of a real-world problem is called a mathematical model of the real-world problem. An algorithm represents some quantitative method used by an analyst to solve the defined

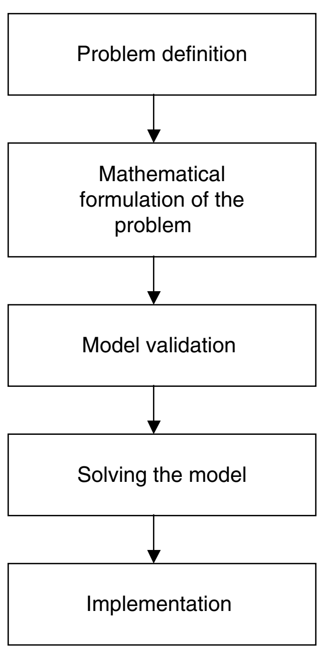

FIGURE 3.1 Problem solving steps.

mathematical model. Algorithms are composed of a set of instructions, which are usually followed in a defined step-by-step procedure. An algorithm produces a feasible solution to a defined model with the goal to find an optimal solution. Optimal solution to the defined problem is the best possible solution among all feasible solutions. Depending on a defined objective function, optimal solution corresponds to maximum revenue, minimum cost, maximum profit, and so on.

3.3 Mathematical Programming

In the past three decades, linear, nonlinear, dynamic, integer, and multiobjective programming have been successfully used to solve various engineering, management, and control problems. Mathematical programming techniques have been used to address problems dealing with the most efficient allocation of limited resources (supplies, capital, labor, etc.) to meet the defined objectives. Typical problems include market share maximization, production scheduling, personnel scheduling and rostering, vehicle routing and scheduling, locating facilities in a network, planning fleet development, etc. Their solutions can be found using one of the mathematical programming methods.

3.3.1 Linear Programming

Let us consider a rent-a-car company operations. The total number of vehicles that the company owns equals 100. The potential clients are offered 2 tariff classes at $150 per week and $100 per week. The potential client pays $100 per week if he or she makes the reservation at least 3 days in advance. We assume that we are able to predict exactly the total number of requests in both client-tariff classes. We expect 70 client requests in the first class and 80 client requests in the second class during the considered time period. We decide to keep at least 10 vehicles for the clients paying higher tariffs. We have to determine the total numbers of vehicles rented in different client tariff classes to reach the maximum company revenue.

Solution:

As we wish to determine the total numbers of vehicles rented in different client tariff classes, the variables of the model can be defined as:

x_1—the total number of vehicles planned to be rented in the first client-tariff class
x_2—the total number of vehicles planned to be rented in the second client-tariff class

Because each vehicle from the first class rents for $150, the total revenue from renting x_1 vehicles is $150x_1$. In the same way, the total company revenue from renting the x_2 vehicles equals $100x_2$. The total company revenue equals the sum of the two revenues, $150x_1 + 100x_2$.

From the problem formulation we conclude that there are specific restrictions on vehicle renting and demand. The vehicle renting restrictions may be expressed verbally in the following way:

- Total number of vehicles rented in both classes together must be less than or equal to the total number of vehicles.
- Total number of vehicles rented in any class must be less than or equal to the total number of client requests.
- Total number of vehicles rented in the first class must be at least 10.
- Total number of vehicles rented in the second class cannot be less than zero (non-negativity restriction).

The following is the mathematical model for rent-a-car revenue management problem:
Maximize

$$F(X) = 150x_1 + 100x_2$$

subject to:

$$\begin{aligned} x_1 + x_2 &\le 100 \\ x_1 &\le 70 \\ x_2 &\le 80 \\ x_1 &\ge 10 \\ x_2 &\ge 0 \end{aligned}$$

In our problem, we allow variables to take the fractional values (we can always round the fractional value to the closest feasible integer value). In other words, all our variables are continuous variables. We also have only *one* objective function. We try to maximize the total company's revenue. Our objective function and all our constraints are linear, meaning that any term is either a constant or a constant multiplied by a variable. Any mathematical model that has one objective function, all continuous variables, linear objective function and all linear constraints is called a linear program (LP). It has been seen through many years that many real-life problems can be formulated as linear programs. Linear programs are usually solved using widely spread Simplex algorithm (there is also an alternative algorithm called Interior Point Method).

As we have only two variables, we can also solve our problem graphically. Graphical method is impractical for mathematical models with more than two variables. To solve the earlier-stated problem graphically, we plot the feasible solutions (solution space) that satisfy all constraints simultaneously. Figure 3.2 shows our solution space.

All feasible values of the variables are located in the first quadrant. This is caused by the following constraints: $x_1 \ge 10$, and $x_2 \ge 0$. The straight-line equations $x_1 = 10, x_1 = 70, x_2 = 80, x_2 = 0$, and $x_1 + x_2 = 100$ are obtained by substituting "≤" by "=" for each constraint. Then, each straight-line is plotted. The region in which each constraint is satisfied when the inequality is put in power is indicated by the direction of the arrow on the corresponding straight line. The resulting solution space of the rent-a-car problem is shown in the Figure 3.3. Feasible points for the problem considered are all points within the boundary or on the boundary of the solution space. The optimal solution is discovered by studying the direction in which the objective function $F = 150\,x_1 + 100\,x_2$ rises. The optimal solution is shown in the Figure 3.3.

The parallel lines in the Figure 3.3 represent the objective function $F = 150\,x_1 + 100\,x_2$. They are plotted by arbitrarily assigning increasing values to F. In this way, it is possible to make conclusions about the slope and the direction in which the total company revenue increases.

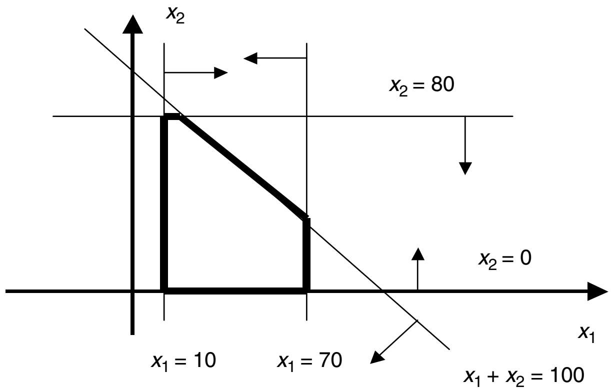

FIGURE 3.2 Solution space of the rent-a-car revenue management problem.

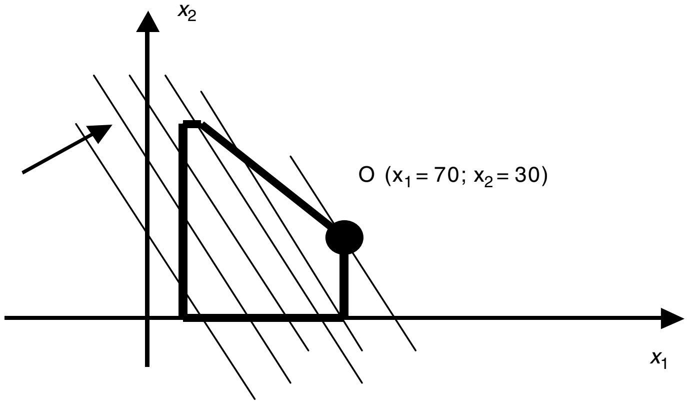

FIGURE 3.3 The optimal solution of the rent-a-car problem.

To discover the optimal solution, we move the revenue line in the direction indicated in Figure 3.3 to the point "*O*" where any further increase in company revenue would create an infeasible solution. The optimal solution happens at the intersection of the following lines:

$$x_1 + x_2 = 100$$
$$x_1 = 70$$

After solving the system of equations we get:

$$x_1 = 70$$
$$x_2 = 30$$

The corresponding rent-a-car company revenue equals:

$$F = 150\, x_1 + 100\, x_2 = 150(70) + 100(30) = 13{,}500$$

The problem considered is a typical resource allocation problem. Linear Programming helps us to discover the best allocation of limited resources. The following is a Linear Programming Model:

Maximize

$$F(X) = c_1x_1 + c_2x_2 + c_3x_3 + \cdots + c_nx_n$$

subject to:

$$\begin{aligned} &a_{11}x_1 + a_{12}x_2 + a_{13}x_3 + \cdots + a_{1n}x_n \le b_1 \\ &a_{21}x_1 + a_{22}x_2 + a_{23}x_3 + \cdots + a_{2n}x_n \le b_2 \\ \\ &a_{m1}x_1 + a_{m2}x_2 + a_{m3}x_3 + \cdots + a_{mn}x_n \le b_m \\ &x_1, x_2, \ldots, x_n \ge 0 \end{aligned} \tag{3.1}$$

The variables $x_1, x_2, \ldots, x_n$ describe level of various economic activities (number of cars rented to the first class of clients, number of items to be kept in the stock, number of trips per day on specific route, number of vehicles assigned to a particular route, etc.).

3.3.2 Integer Programming

Analysts frequently realize that some or all of the variables in the formulated linear program must be integers. This means that some variables or all take exclusively integer values. To make the formulated problem easier, analysts often allow these variables to take fractional values. For example, analysts know that the number of first class clients must be in the range between 30 and 40. Linear program could produce the "optimal solution" that tells us that the number of first class clients equals 37.8. In this case, we can neglect the fractional part, and we can decide to protect 37 (or 38) cars for the first class clients. In this way, we are making small numerical error, but we are capable to easily solve the problem.

In some other situations, it is not possible for analysts to behave in this way. Imagine that we have to decide about a new warehouse layout. You must choose one out of numerous generated alternatives. This is kind of "yes/no" ("1/0") decision: "Yes" if the alternative is chosen, "No," otherwise. In other words, we can introduce binary variables into the analysis. The variable has value 1 if the *i*-th alternative is chosen and value 0 otherwise. The value 0.7 of the variable means nothing to us. We are not able to decide about the best warehouse layout if the variables take fractional values. When we solve problems similar to the warehouse layout problem we work exclusively with integer variables. These kinds of problems are known as integer programs, and corresponding area is known as Integer Programming. Integer programs usually describe the problems in which one, or more, alternatives must be selected from a finite set of generated alternatives. Problems of determining the best schedule of activities, finding the optimal set of vehicle routes, or discovering the shortest path in a transportation network are typical problems that are formulated as integer programs. There are also problems in which some variables can take only integer values, while some other variables can take fractional values. These problems are known as mixed-integer programs. It is much harder to solve Integer Programming problems than Linear Programming problems.

The following is the Integer Programming Model formulation:

Maximize

$$F(X) = \sum_{j=1}^{n} c_j x_j$$

subject to:

$$\begin{aligned} &\sum_{j=1}^{n} a_{ij} x_j \le b_i \qquad \textit{for } i = 1, 2, \ldots, m \\ &0 \le x_j \le u_j \qquad \textit{integer for } j = 1, 2, \ldots, n \end{aligned} \tag{3.2}$$

There are numerous software systems that solve linear, integer, and mixed-integer linear programs (CPLEX, Excel and Quattro Pro Solvers, FortMP, LAMPS, LINDO, LINGO, MILP88, MINTO, MIPIII, MPSIII, OML, OSL).

A combinatorial explosion of possible solutions characterizes many of the Integer Programming problems. In cases when the number of integer variables in a considered problem is very large, finding optimal solution becomes very difficult, if not impossible. In such cases, various heuristic algorithms are used to discover "good" solutions. These algorithms do not guarantee the optimal solution discovery.

3.4 Heuristic Algorithms

Many logistic problems are combinatorial by nature. Combinatorial optimization problems could be solved by exact or by heuristic algorithms.

The exact algorithms always find the optimal solution(s). The wide usage of the exact algorithms is limited by the computer time needed to discover the optimal solution(s). In some cases, this computer time is enormously large.

The word "heuristic" has its roots in Greek word "ευρισκω" that means "to discover," or "to find." Heuristic algorithm could be described as a combination of science, invention, and problem solving skills. In essence, a heuristic algorithm represents procedure invented and used by the analyst(s) in order to "travel" (search) through the space of feasible solutions. Good heuristics algorithm should generate quality solutions in an acceptable computer time. Complex logistic problems of big dimensions are usually solved with the help of various heuristic algorithms. Good heuristic algorithms are capable of discovering optimal solutions for some problem instances, but heuristic algorithms do not guarantee optimal solution discovery.

There are few reasons why heuristic algorithms are widely used. Heuristic algorithms are used to solve the problems in situations in which exact algorithm would require solution time that increases exponentially with a size of a problem. For example, in case of a problem that is characterized by 3000 binary variables (that can take values 0 or 1), the number of potential solutions is equal to 2^{3000}.

In some cases, the costs of using the exact algorithm are much higher than the potential benefits of discovering the optimal solution. Consequently, in such situations analysts usually use various heuristic algorithms.

It could frequently happen that the problem considered is not well "structured." This means that all relevant information is not known by the analyst, and that the objective function(s) and constraints are not precisely defined. An attempt to find the "optimal" solution for the ill-defined problem could generate the "optimal" solution that is in reality poor solution to the real problem.

The decision-makers are frequently interested in discovering "satisfying" solution of real-life problems. Obtaining adequate information about considered alternatives is usually very costly. At the same time, the consequences of many possible decisions are not known precisely causing decision-makers to come across with a course of action that is acceptable, sufficient, and logical. In other words, "satisfying" solution represents the solution that is satisfactory to the decision-makers. Satisfactory solution(s) could be generated by various heuristic algorithms, after limited search of the solution space.

Great number of real-life logistic problems could be solved only by heuristic algorithms. Large number of heuristic algorithms are based on relatively simple ideas, and many of them have been developed without previous mathematical formulation of the problem.

3.4.1 "Classical" Heuristic Algorithms

The greedy and interchange heuristics are the widely used heuristic algorithms. Let us clarify the basic principles of these algorithms by analyzing the traveling salesman problem (TSP). The TSP is one of the most well-known problems in OR and computer science. This problem can be defined as follows: Find the shortest itinerary which starts in a specific node, goes through all other nodes exactly once, and finishes in the starting node. In different traffic, transportation, and logistic problems, the traveling salesman can represent airplanes, boats, trucks, buses, crews, etc. Vehicles visiting nodes can deliver or pick up goods, or simultaneously perform pick up and delivery.

A typical solution process of the TSP is stepwise as in the following: (a) First an initial tour is constructed; (b) Any remaining unvisited nodes are inserted; (c) The created tour is improved. There are many developed algorithms for each step.

Before discussing various heuristic algorithms, let us define the "scenario" of the TSP. A traveling salesman starting and finishing its tour at one fixed point must visit $(n - 1)$ points. The transportation network connecting these n points is completely connected. This means that it is possible to reach any node from any other node, directly, without going through the other nodes (an air transportation network is a typical example of this type of network). The shortest distance between any two nodes equals the length of the branches between these nodes.

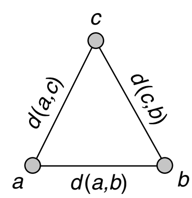

FIGURE 3.4 "Triangular inequality."

From this, it is certain that the following inequality is satisfied:

$$d(a,b) < d(a,c) + d(c,b) \tag{3.3}$$

for any three nodes a, b, and c.

We also assume that the matrix of shortest distances between the nodes is symmetrical. The nodes a, b, and c are shown in Figure 3.4.

3.4.2 Heuristic Algorithm Based on Random Choice

The TSP could be easily solved by the following simple heuristic algorithm:

Step 1: Arbitrarily choose starting node.
Step 2: Randomly choose the next node to be included in the traveling salesman tour.
Step 3: Repeat Step 2 until all nodes are chosen. Connect the first and the last node of the tour.

This algorithm is based on the idea of random choice. The next node to be included in the partial traveling salesman tour is chosen at random. In other words, the sequence of nodes to be visited is generated at random. It is intuitively clear that one cannot expect that this algorithm would give very good results, as it does not use any relevant information when choosing the next node that is to be included in the tour. On the other hand generating sequences of nodes at random can be repeated two, three, …, or ten thousand times. The repetition of generating various solutions represents the main power of this kind of an algorithm. Obviously, the decision-maker can choose the best solution among all solutions generated at random. The greater the number of solutions generated, the higher the probability that one can discover a "good" solution.

3.4.3 "Greedy" Heuristic Algorithms

"Greedy" heuristic algorithms build the solution of the studied problem in a step-by-step procedure. In every step of the procedure the value is assigned to one of the variables in order to maximally improve the objective function value. In every step, the greedy algorithm is looking for the best current solution with no look upon future cost or consequences. Greedy algorithms use local information available in every step. The fundamental concept of greedy algorithms is similar to the "Hill-climbing" technique. In case of "Hill-climbing" technique the current solution is continuously replaced by the new solution until it is not possible to produce further improvements in the objective function value. "Greedy" algorithms and the "Hill-climbing" technique are similar to the hiker who is trying to come to the mountaintop by never going downwards (Fig. 3.5).

As it can be seen from Figure 3.5, hiker's wish to never move down while climbing, can trap him or her at some of the local peaks (local maximums), and prevent him or her from reaching the mountaintop (global maximum). "Greedy" algorithms and the "Hill-climbing" technique consider only local improvements.

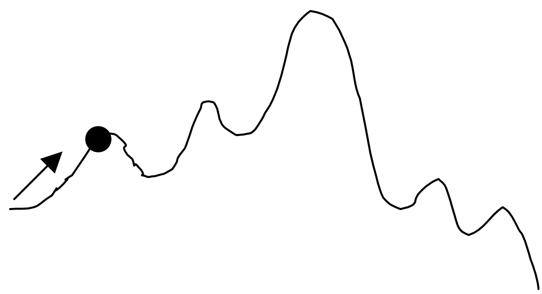

FIGURE 3.5 Hiker who is trying to come to the mountaintop by going up exclusively.

The Nearest Neighbor (NN) heuristic algorithm is a typical representative of "Greedy" algorithms. This algorithm, which is used to generate the traveling salesman tour, is composed of the following algorithmic steps:

Step 1: Arbitrarily (or randomly) choose a starting node in the traveling salesman tour.
Step 2: Find the nearest neighbor of the last node that was included in the tour. Include this nearest neighbor in the tour.
Step 3: Repeat Step 2 until all nodes are not included in the traveling salesman tour. Connect the first and the last node of the tour.

The NN algorithm finds better solutions than the algorithm based on random choice, as it uses the information related to the distances between nodes.

Let us find the traveling salesman tour starting and finishing in node 1, using NN heuristic algorithm (Fig. 3.6). The distances between all pairs of nodes are given in the Table 3.1.

The route must start in node 1. The node 2 is the NN of node 1. We include this NN in the tour. The current tour reads: (1, 2). Node 3 is the NN of node 2. We include this NN in the tour. The updated tour reads: (1, 2, 3). Continuing in this way, we obtain the final tour that reads: (1, 2, 3, 4, 5, 6, 7, 1). The final tour is shown in Figure 3.7.

Both algorithms shown ("random choice" and "greedy") repeat the specific procedure a certain number of times unless a solution has been generated. Many of the heuristic algorithms are based on a specific procedure that is repeated until solution is generated.

When applying "greedy" approach, the analyst is forced, after a certain number of steps, to start to connect the nodes (in case of TSP) quite away from each other. Connecting the nodes distant from each other is forced by previous connections that significantly decrease the number of possible connections left.

3.4.4 Exchange Heuristic Algorithms

Exchange heuristic algorithms are based on the idea of interchange and they are widely used. The idea of interchange is the idea to start with the existing solution and check if this solution could be improved.

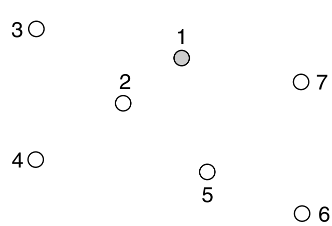

FIGURE 3.6 Network in which a traveling salesman tour should be created using NN heuristic algorithm.

TABLE 3.1 The Distances between All Pairs of Nodes

	1	**2**	**3**	**4**	**5**	**6**	**7**
1	0	75	135	165	135	180	90
2	75	0	90	105	135	210	150
3	135	90	0	150	210	300	210
4	165	105	150	0	135	210	210
5	135	135	210	135	0	90	105
6	180	210	300	210	90	0	120
7	90	150	210	210	105	120	0

Exchange heuristic algorithm first creates or selects an initial feasible solution in some arbitrary way (randomly or using any other heuristic algorithm), and then tries to improve the current solution by specific exchanges within the solution.

The good illustration of this concept is two-optimal tour (2-OPT) heuristic algorithms for the TSP [3-OPT and *k*-optimal tour (*k*-OPT) algorithms are based on the same idea]. Within the first step of the 2-OPT algorithm, an initial tour is created in some arbitrary way (randomly or using any other heuristic algorithm). The two links are then broken (Fig. 3.8). The paths that are left are joined so as to form a new tour. The length of the new tour is compared with the length of the old tour. If the new tour length is less than the old tour length, the new tour is retained. In a systematic way, two links are broken at a time, paths are joined, and comparison is made. Eventually, a tour is found whose total length cannot be decreased by the interchange of any two links. Such a tour is known as two-optimal tour (2-OPT).

After breaking links (a, j) and (d, e), the node a has to be connected with node e. The node d should be connected with node j. The connection between node a and node d, as well as the connection between node j and node e would prevent creating the traveling salesman tour. In case of 3-OPT algorithm in a systematic way three links are broken, new tour is created, tour lengths are compared, and so on.

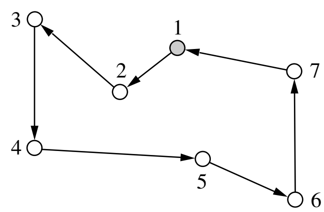

FIGURE 3.7 Traveling salesman tour obtained by the *NN* heuristic algorithm.

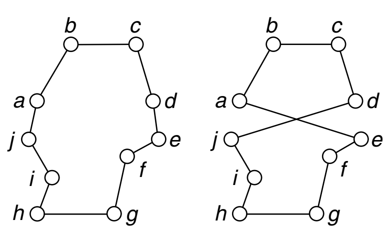

FIGURE 3.8 Interchange of two links during 2-OPT algorithm.

2-OPT algorithm is composed of the following algorithmic steps:

Step 1: Create an initial traveling salesman tour.
Step 2: The initial tour is the following tour: $(a_1, a_2, ..., a_n, a_1)$. The total length of this tour is equal to D. Set $i = 1$.
Step 3: $j = i + 2$.
Step 4: Break the links (a_i, a_{i+1}) and (a_j, a_{j+1}) and create the new traveling salesman tour. This tour is the following tour: $(a_1, a_2, ..., a_i, a_j, ..., a_{i+1}, a_{j+1}, a_{j+2}, ..., a_1)$. If the length of the new tour is less than D, than keep this tour and return to Step 2. Otherwise go to Step 5.
Step 5: Set $j = j + 1$. If $j \le n$ go to Step 4. In the opposite case, increase i by 1 ($i = i + 1$). If $i \le n - 2$ go to Step 3. Otherwise, finish with the algorithm.

By using the 2-OPT algorithm, we will try to create the traveling salesman tour for the network shown in Figure 3.6. The distances between nodes are given in Table 3.1. The traveling salesman should start his trip from node 1. The initial tour shown in Figure 3.7 is generated by the NN algorithm. It was not possible to decrease the total length of the initial tour by interchanging of any two links (Table 3.2). Our initial tour is 2-OPT.

The k-opt algorithm for the TSP assumes breaking k links in a systematic way, joining the paths, and performing the comparison. Eventually a tour is found whose total length cannot be decreased by the interchange of any k links. Such a tour is known as k-OPT.

3.4.5 Decomposition Based Heuristic Algorithms

In some cases it is desirable to decompose the problem considered into smaller problems (subproblems). In the following step every subproblem is solved separately. Final solution of the original problem is then obtained by "assembling" the subproblem solutions. We illustrate this solution approach in case of the standard vehicle routing problem (VRP).

There are n nodes to be served by homogeneous fleet (every vehicle has identical capacity equal to V). Let us denote by v_i ($i = 1, 2, ..., n$) demand at node i. We also denote by D vehicle depot (all vehicles start their trip from D, serve certain number of nodes and finish route in node D).

Vehicle capacity V is greater than or equal to demand at any node. In other words, every node could be served by one vehicle, that is, vehicle routes are composed of one or more nodes.

TABLE 3.2 Steps in the 2-OPT Algorithm

Broken Links	New Traveling Salesman Tour	Tour Length
(1, 2), (3, 4)	(1, 3, 2, 4, 5, 6, 7, 1)	765
(1, 2), (4, 5)	(1, 4, 3, 2, 5, 6, 7, 1)	840
(1, 2), (5, 6)	(1, 5, 3, 4, 2, 6, 7, 1)	1020
(1, 2), (6, 7)	(1, 6, 3, 4, 5, 2, 7, 1)	1140
(1, 2), (7, 1)	(1, 7, 3, 4, 5, 6, 2, 1)	960
(2, 3), (4, 5)	(1, 2, 4, 3, 5, 6, 7, 1)	840
(2, 3), (5, 6)	(1, 2, 5, 4, 3, 6, 7, 1)	1005
(2, 3), (6, 7)	(1, 2, 6, 4, 5, 3, 7, 1)	1140
(2, 3), (7, 1)	(1, 2, 7, 4, 5, 6, 3, 1)	1095
(3, 4), (5, 6)	(1, 2, 3, 5, 4, 6, 7, 1)	930
(3, 4), (6, 7)	(1, 2, 3, 6, 5, 4, 7, 1)	990
(3, 4), (7, 1)	(1, 2, 3, 7, 5, 6, 4, 1)	945
(4, 5), (6, 7)	(1, 2, 3, 4, 6, 5, 7, 1)	810
(4, 5), (7, 1)	(1, 2, 3, 4, 7, 6, 5, 1)	870
(5, 6), (7, 1)	(1, 2, 3, 4, 5, 7, 6, 1)	855

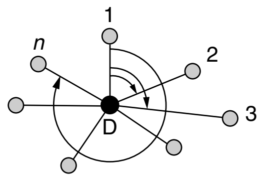

FIGURE 3.9 Sweep algorithm.

Problem to be solved could be described in the following way: Create set of vehicle routes in such a way as to minimize the total distance traveled by all vehicles.

Real-life VRP could be very complex. One or more of the following characteristics could appear when solving some of the real-life VRP: (a) Some nodes must be served within prescribed time intervals (time windows); (b) Service is performed by heterogeneous fleet of vehicles (vehicles have different capacities); (c) Demand at nodes is not known in advance; (d) There are few depots in the network.

The Sweep algorithm is one of the classical heuristic algorithms for the VRP. This algorithm is applied to polar coordinates, and the depot is considered to be the origin of the coordinate system. Then the depot is joined with an arbitrarily chosen point that is called the *seed point*. All other points are joined to the depot and then aligned by increasing angles that are formed by the segments that connect the points to the depot and the segment that connects the depot to the seed point. The route starts with the seed point, and then the points aligned by increasing angles are included, respecting given constraints. When a point cannot be included in the route as this would violate a certain constraint, this point becomes the seed point of a new route, and so on. The process is completed when all points are included in the routes (Fig. 3.9).

In case when a large number of nodes need to be served, the Sweep algorithm should be used within the "clustering-routing" approach. In this case, considering clockwise direction, the ratio of cumulative demand and vehicle capacity should be checked (including all other constraints). The node that cannot be included because of the violation of vehicle capacity or other constraints becomes the first node in another cluster. In this way, the whole region is divided into clusters (zones). In the following step, VRP is solved within each cluster separately. Clustering is completed when all nodes are assigned to clusters (Fig. 3.10). It is certain that one vehicle can serve all nodes within one cluster. In this way, the VRP is transformed into few TSP.

The final solution depends on a choice of the seed point. By changing locations of the seed point it is possible to generate various sets of vehicle routes. For the final solution the set of routes with minimal total length should be chosen.

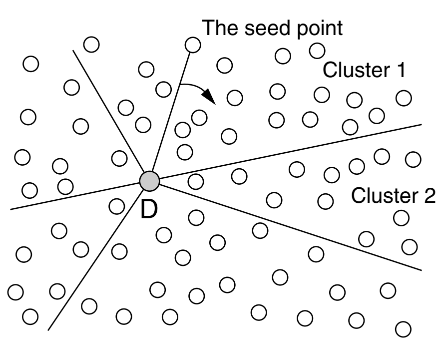

FIGURE 3.10 Clustering by Sweep algorithm.

3.5 Algorithms' Complexity

Various heuristic algorithms could be used to solve a specific problem. Decision-makers prefer to use algorithms that have relatively short CPU time (execution time) and provide reasonably good solutions. One might ask, which one of the developed algorithms is better for solving the TSP? The execution time highly depends on the CPU time, programming language, speed of a computer, etc. To objectively compare various algorithms, a measurement of algorithms' complexity has been proposed that is independent of all computer types and programming languages. The "goodness" of the algorithm is highly influenced by the algorithm's complexity. The complexity of the algorithm is usually measured through the total number of elementary operations (additions, subtractions, comparisons, etc.) that the algorithm requires to solve the problem under the worst case conditions.

Let us assume that we have to solve the TSP. We denote by n the total number of nodes. We also denote by E the total number of elementary operations. Let us assume that E equals:

$$E = 4n^4 + 5n^3 + 2n + 7 \tag{3.4}$$

As n increases, the E value is largely determined by the term n^4. We can describe this fact by using the "O-notation." The "O-notation" is used to describe the algorithms' complexity. In the considered example, we write that the algorithm's complexity is $O(n^4)$, or that solution time is of the order $O(n^4)$. The "O-notation" neglects smaller terms, as well as proportional factors. It could happen that for small input sizes an inefficient algorithm may be faster than an efficient algorithm. Practically, the comparison of the algorithms based on "O-notation" is practical only for large input sizes. For example, the algorithm whose complexity is $O(n^2)$ is better than the algorithm whose complexity is $O(n^3)$.

Many real-life problems can be solved by the algorithms whose solution time grows as a polynomial function of the problem size. We call such algorithms polynomial algorithms. The problems that can be solved by polynomial algorithms are considered as *easy problems*. Large instances of easy problems can be solved in "reasonable" computer times using an adequate algorithm and a "fast" computer.

All optimization problems can be classified into two sets. By P we denote the set of problems that can be solved by polynomial algorithms. All other problems, whose solution is difficult or impossible, belong to the set that is called *NP-Complete*. No polynomial time algorithms have been created for the problems that belong to the set *NP-Complete*.

Polynomial algorithms are "good" algorithms [e.g., the algorithms whose complexity is $O(n^2)$, $O(n^5)$, or $O(n^6)$]. The algorithm whose complexity is $O(n \log n)$ also belongs to the class of polynomial algorithms, as $(n \log n)$ is bounded by (n^2). Developing appropriate polynomial algorithm could be, in some cases difficult, time consuming, or costly.

Non-polynomial algorithms [e.g., the algorithms whose complexity is $O(3^n)$ or $O(n!)$] are not "good" algorithms. When the algorithms' complexity is, for example, $O(3^n)$, we see, that the function in the parentheses is *exponential* in n. One might ask, "Could a faster computer help us to successfully solve "difficult" problems?" The development of faster computers in the future will enable us to solve larger sizes of these problems; however, there is no indication that we will be able to find optimal solutions in these cases. Every specific problem should be carefully studied. In some cases, it is not an easy task to recognize an "easy" problem and to make the decision regarding the solution approach (optimization vs. heuristic). All heuristic algorithms are evaluated according to the quality of the solutions generated, as well as computer time needed to reach the solution. In other words, good heuristics algorithm should generate quality solutions in an acceptable computer time. Simplicity and easiness to implement these algorithms are the additional criteria that should be taken into account when evaluating a specific heuristic algorithm.

Heuristic algorithms do not guarantee the optimal solution discovery. The closer the solution produced is to the optimal solution, the better the algorithm. It is an usual practice to perform "Worst Case Analysis," as well as "Average Case Analysis" for every considered heuristic algorithm. Worst Case

Analysis assumes generating special numerical examples (that appear rarely in real life) that can show the worst results generated by the proposed heuristic algorithm. For example, we can conclude that the worst solution generated by the proposed heuristic algorithm is 5% far from the optimal solution. Within the Average Case Analysis, a great number of typical examples are usually generated and analyzed. By performing statistical analysis related to the solutions generated, the conclusions are derived about the quality of the solutions generated in the "average case." The more real-life examples are tested, the easier it is to evaluate specific heuristic algorithm.

3.6 Randomized Optimization Techniques

Many heuristic techniques that have been developed are capable of solving only a specific problem, whereas metaheuristics can be defined as general combinatorial optimization techniques. These techniques are designed to solve many different combinatorial optimization problems. The developed metaheuristics are based on local search techniques, or on population search techniques. Local search-based metaheuristics (Simulated Annealing, Tabu Search, etc.) are characterized by an investigation of the solution space in the neighborhood of the current solution. Each step in these metaheuristics represents a move from the current solution to another potentially good solution in the current solution's neighborhood. In case of a population search, as opposed to traditional search techniques, the search is run in parallel from a population of solutions. These solutions are combined and the new generation of solutions is generated. Each new generation of solutions is expected to be "better" than the previous one.

3.6.1 Simulated Annealing Technique

The simulated annealing technique is one of the methods frequently used in solving complex combinatorial problems. This method is based on the analogy with certain problems in the field of statistical mechanics. The term, simulated annealing, comes from the analogy with physical processes. The process of annealing consists in decreasing the temperature of a material, which in the beginning of the process is in the molten state, until the lowest state of energy is attained. At certain points during the process the so-called thermal equilibrium is reached. In case of physical systems we seek to establish the order of particles that has the lowest state of energy. This process requires that the temperatures at which the material remains for a while are previously specified.

The basic idea of simulated annealing consists in performing small perturbations (small alterations in the positions of particles) in a random fashion and computing the energy changes between the new and the old configurations of particles, ΔE. In case when $\Delta E < 0$, it can be concluded that the new configuration of particles has lower energy. The new configuration then becomes a new initial configuration for performing small perturbations. The case when $\Delta E > 0$ it means that the new configuration has higher energy. However, in this case the new configuration should not be automatically excluded from the possibility of becoming a new initial configuration. In physical systems, "jumps" from lower to higher energy levels are possible. The system has higher probability to "jump" to a higher energy state when the temperature is higher. As the temperature decreases, the probability that such a "jump" will occur diminishes. Probability P that at temperature T the energy will increase by ΔE equals:

$$P = e^{-\frac{\Delta E}{T}} \tag{3.5}$$

The decision whether a new configuration of particles for which $\Delta E > 0$ should be accepted as a new initial configuration is made upon the generation of a random number r from the interval [0, 1]. Generated random number is uniformly distributed. If $r < P$, the new configuration is accepted as a new initial configuration. In the opposite case, the generated configuration of particles is excluded from consideration.

In this manner, a successful simulation of attaining thermal equilibrium at a particular temperature is accomplished. Thermal equilibrium is considered to be attained when, after a number of random perturbations, a significant decrease in energy is not possible. Once thermal equilibrium has been attained, the temperature is decreased, and the described process is repeated at a new temperature.

The described procedure can also be used in solving combinatorial optimization problems. A particular configuration of particles can be interpreted as one feasible solution. Likewise, the energy of a physical system can be interpreted as the objective function value, while temperature assumes the role of a control parameter. The following is a pseudo-code for simulated annealing algorithm:

Select an initial state $i \in S$;
Select an initial temperature $T > 0$;
Set temperature change counter $t := 0$;
Repeat
    Set repetition counter $n := 0$;
    Repeat
        Generate state j, a neighbor of i;
        Calculate $\Delta E := f(j) - f(i)$
        if $\Delta E < 0$ then $i := j$
        else if random (0, 1) < exp ($-\Delta E$/T) then $i := j$;
        Inc(n);
    Until $n = N(t)$;
    Inc(t);
    $T := T(t)$;
Until stopping criterion true.
where:
S—finite solution set,
i—previous solution,
j—next solution,
$f(x)$—criteria value for solution x, and
$N(t)$—number of perturbations at the same temperature.

It has been a usual practice that during the execution of the simulated annealing algorithm, the best solution obtained thus far is always remembered. The simulated annealing algorithm differs from general local search techniques as it allows the acceptance of improving as well as nonimproving moves. The benefit of accepting nonimproving moves is that the search does not prematurely converge to a local optimum and it can explore different regions of the feasible space.

3.6.2 Genetic Algorithms

Genetic algorithms represent search techniques based on the mechanics of nature selection used in solving complex combinatorial optimization problems. These algorithms were developed by analogy with Darwin's theory of evolution and the basic principle of the "survival of the fittest." In case of genetic algorithms, as opposed to traditional search techniques, the search is run in parallel from a population of solutions. In the first step, various solutions to the considered maximization (or minimization) problem are generated. In the following step, the evaluation of these solutions, that is, the estimation of the objective (cost) function is made. Some of the "good" solutions yielding a better "fitness" (objective function value) are further considered. The remaining solutions are eliminated from consideration. The chosen solutions undergo the phases of *reproduction*, *crossover*, and *mutation*. After that, a new generation of solutions is produced to be followed by a new one, and so on. Each new generation is expected to be "better" than the previous one. The production of new generations is stopped when a prespecified stopping condition is satisfied. The final solution of the considered problem is the best solution generated

TABLE 3.3 Encoded Values of Variable x

String	Value of Variable x	String	Value of Variable x
0000	$0 = 0*2^3 + 0*2^2 + 0*2^1 + 0*2^0$	1000	$8 = 1*2^3 + 0*2^2 + 0*2^1 + 0*2^0$
0001	$1 = 0*2^3 + 0*2^2 + 0*2^1 + 1*2^0$	1001	$9 = 1*2^3 + 0*2^2 + 0*2^1 + 1*2^0$
0010	$2 = 0*2^3 + 0*2^2 + 1*2^1 + 0*2^0$	1010	$10 = 1*2^3 + 0*2^2 + 1*2^1 + 0*2^0$
0011	$3 = 0*2^3 + 0*2^2 + 1*2^1 + 1*2^0$	1011	$11 = 1*2^3 + 0*2^2 + 1*2^1 + 1*2^0$
0100	$4 = 0*2^3 + 1*2^2 + 0*2^1 + 0*2^0$	1100	$12 = 1*2^3 + 1*2^2 + 0*2^1 + 0*2^0$
0101	$5 = 0*2^3 + 1*2^2 + 0*2^1 + 1*2^0$	1101	$13 = 1*2^3 + 1*2^2 + 0*2^1 + 1*2^0$
0110	$6 = 0*2^3 + 1*2^2 + 1*2^1 + 0*2^0$	1110	$14 = 1*2^3 + 1*2^2 + 1*2^1 + 0*2^0$
0111	$7 = 0*2^3 + 1*2^2 + 1*2^1 + 1*2^0$	1111	$15 = 1*2^3 + 1*2^2 + 1*2^1 + 1*2^0$

during the search. In case of genetic algorithms an encoded parameter set is used. Most frequently, binary coding is used. The set of decision variables for a given problem is encoded into a bit string (chromosome, individual).

Let us explain the concept of encoding in case of finding the maximum value of function $f(x) = x^3$ in the domain interval of x ranging from 0 to 15. By means of binary coding, the observed values of variable x can be presented in strings of the length 4 (as $2^4 = 16$). Table 3.3 shows 16 strings with corresponding decoded values.

We assume that in the first step the following four strings were randomly generated: 0011, 0110, 1010, and 1100. These four strings form the initial population P(0). In order to make an estimation of the generated strings, it is necessary to decode them. After decoding, we actually obtain the following four values of variable x: 3, 6, 10, and 12. The corresponding values of function $f(x) = x^3$ are equal to $f(3) = 27$, $f(6) = 216$, $f(10) = 1000$ and $f(12) = 1728$. As can be seen, string 1100 has the best fitness value.

Genetic algorithms is a procedure where the strings with better fitness values are more likely to be selected for mating. Let us denote by f_i the value of the objective function (fitness) of string i. The probability p_i for string i to be selected for mating is equal to the ratio of f_i to the sum of all strings' objective function values in the population:

$$p_i = \frac{f_i}{\sum_j f_j} \tag{3.6}$$

This type of reproduction, that is, selection for mating represents a proportional selection known as the "roulette wheel selection." (The sections of roulette are in proportion to probabilities p_i.) In addition to the "roulette wheel selection," several other ways of selection for mating have been suggested in the literature.

In order to generate the next population P(1), we proceed to apply the other two genetic operators to the strings selected for mating. Crossover operator is used to combine the genetic material. At the beginning, pairs of strings (parents) are randomly chosen from a set of previously selected strings. Later, for each selected pair the location for crossover is randomly chosen. Each pair of parents creates two offsprings (Fig. 3.11).

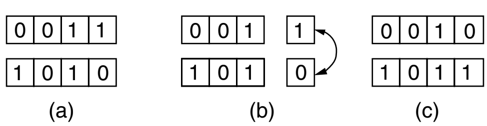

FIGURE 3.11 A single-point crossover operator: (a) two parents (b) randomly chosen location is before the last bit (c) two offsprings.

After completing crossover, the genetic operator mutation is used. In case of binary coding, mutation of a certain number of genes refers to the change in value from 1 to 0 or vice versa. It should be noted that the probability of mutation is very small (of order of magnitude 1/1000). The purpose of mutation is to prevent an irretrievable loss of the genetic material at some point along the string. For example, in the overall population a particularly significant bit of information might be missing (e.g., none of the strings have 0 at the seventh location), which can considerably influence the determination of the optimal or near-optimal solution. Without mutation, none of the strings in all future populations could have 0 at the seventh location. Nor could the other two genetic operators help to overcome the given problem. Having generated population P(1) [which has the same number of members as population P(0)], we proceed to use the operators reproduction, crossover, and mutation to generate a sequence of populations P(2), P(3), and so on.

In spite of modifications that may occur in some genetic algorithms (regarding the manner in which the strings for reproduction are selected, the manner of doing crossover, the size of population that depends on the problem being optimized, and so on), the following steps can be defined within any genetic algorithm:

Step 1: Encode the problem and set the values of parameters (decision variables).

Step 2: Form the initial population P(0) consisting of n strings. (The value of n depends on the problem being optimized.) Make an evaluation of the fitness of each string.

Step 3: Considering the fact that the selection probability is proportional to the fitness, select n parents from the current population.

Step 4: Randomly select a pair of parents for mating. Create two offsprings by exchanging strings with the one-point crossover. To each of the created offsprings, apply mutation. Apply crossover and mutation operators until n offsprings (new population) are created.

Step 5: Substitute the old population of strings with the new population. Evaluate the fitness of all members in the new population.

Step 6: If the number of generations (populations) is smaller than the maximal prespecified number of generations, go back to Step 3. Otherwise, stop the algorithm. For the final solution choose the best string discovered during the search.

3.7 Fuzzy Logic Approach to Dispatching in Truckload Trucking

3.7.1 Basic Elements of Fuzzy Sets and Systems

In the classic theory of sets, very precise bounds separate the elements that belong to a certain set from the elements outside the set. For example, if we denote by A the set of signalized intersections in a city, we conclude that every intersection under observation belongs to set A if it has a signal. Element x's membership in set A is described in the classic theory of sets by the membership function $\mu_A(x)$, as follows:

$$\mu_A(x) = \begin{cases} 1, \text{if and only if } x \text{ is member of A} \\ 0, \text{if and only if } x \text{ is not member of A} \end{cases} \tag{3.7}$$

Many sets encountered in reality do not have precisely defined bounds that separate the elements in the set from those outside the set. Thus, it might be said that waiting time of a vessel at a certain port is "long." If we denote by A the set of "long waiting time at a port," the question logically arises as to the bounds of such a defined set. In other words, we must establish which element belongs to this set. Does a waiting time of 25 hours belong to this set? What about 15 hours or 90 hours?

The membership function of fuzzy set can take any value from the closed interval [0, 1]. Fuzzy set **A** is defined as the set of ordered pairs **A** = {x, $\mu_A(x)$}, where $\mu_A(x)$ is the grade of membership of element x in set **A**. The greater $\mu_A(x)$, the greater the truth of the statement that element x belongs to set **A**.

Fuzzy sets are often defined through membership functions to the effect that every element is allotted a corresponding grade of membership in the fuzzy set. Let us note fuzzy set **C**. The membership function that determines the grades of membership of individual elements x in fuzzy set **C** must satisfy the following inequality:

$$0 \leq \mu_C(x) \leq 1 \qquad \forall x \in X \tag{3.8}$$

Let us note fuzzy set **A**, which is defined as "travel time is approximately 30 hours." Membership function $\mu_A(t)$, which is subjectively determined is shown in Figure 3.12.

A travel time of 30 hours has a grade of membership of 1 and belongs to the set "travel time is approximately 30 hours." All travel times within the interval of 25–35 h are also members of this set because their grades of membership are greater than zero. Travel times outside this interval have grades of membership equal to zero.

Let us note fuzzy sets **A** and **B** defined over set X. Fuzzy sets **A** and **B** are equal (**A** = **B**) if and only if $\mu_A(x) = \mu_B(x)$ for all elements of set X.

Fuzzy set **A** is a subset of fuzzy set **B** if and only if $\mu_A(x) \leq \mu_B(x)$ for all elements x of set X. In other words, **A** ⊂ **B** if, for every x, the grade of membership in fuzzy set **A** is less than or equal to the grade of membership in fuzzy set **B**.

The intersection of fuzzy sets **A** and **B** is denoted by **A** ∩ **B** and is defined as the largest fuzzy set contained in both fuzzy sets **A** and **B**. The intersection corresponds to the operation "and." Membership function $\mu_{A \cap B}(x)$ of the intersection **A** ∩ **B** is defined as follows:

$$\mu_{A \cap B}(x) = \min\{\mu_A(x), \mu_B(x)\} \tag{3.9}$$

The union of fuzzy sets **A** and **B** is denoted by **A** ∪ **B** and is defined as the smallest fuzzy set that contains both fuzzy set **A** and fuzzy set **B**. The membership function $\mu_{A \cup B}(x)$ of the union **A** ∪ **B** of fuzzy sets **A** and **B** is defined as follows:

$$\mu_{A \cup B}(x) = \max\{\mu_A(x), \mu_B(x)\} \tag{3.10}$$

Fuzzy logic systems arise from the desire to model human experience, intuition, and behavior in decision-making. Fuzzy logic (approximate reasoning, fuzzy reasoning) is based on the idea of the possibility of a decison-making based on imprecise, qualitative data by combining descriptive linguistic rules. Fuzzy rules include descriptive expressions such as small, medium, or large used to categorize the linguistic (fuzzy) input and output variables. A set of fuzzy rules, describing the control strategy of the operator (decision-maker) forms a fuzzy control algorithm, that is, approximate reasoning algorithm, whereas the linguistic expressions are represented and quantified by fuzzy sets.

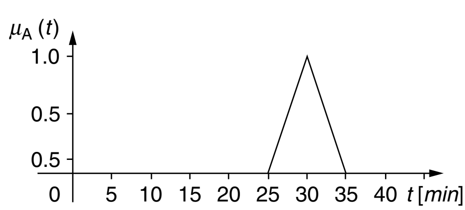

FIGURE 3.12 Membership function $\mu_A(t)$ of fuzzy set **A**.