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Review

A Decade of Forest Engineering: Achievements and Future Directions

Raffaele Spinelli [1,2,*], Rien Visser [3] and Han-Sup Han [4]

[1] CNR IBE, Via Madonna del Piano 10, I-50019 Sesto Fiorentino, Italy
[2] University of the Sunshine Coast, Sippy Downs, QLD 4556 Brisbane, Australia
[3] University of Canterbury, 8140 Christchurch, New Zealand
[4] Northern Arizona University, Flagstaff, AZ 86011, USA
[*] Correspondence: spinelli@ivalsa.cnr.it; Tel.: +39-055-5225641

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Abstract: Research highlights: Through a broad review of literature and practices, this paper has helped confirm Forest Engineering as a unique discipline by providing definition, highlighting achievements of the last decade and suggesting future directions. Background and Objectives: Forest Engineering is a study program offered by many universities worldwide. It is also the main subject of three international scientific journals, three important scientific conferences and a division of the International Union of Forestry Research Organizations. That points at a strong interest, a general common understanding and a strong local diversification. The paper aims to suggest generally valid definitions, while offering a description of the main achievements and a hypothesis about future directions. Results: The review identified examples that include higher-level mechanization, commencement of automation and system optimization, and specifically the emerging field of biomass and bioenergy integration as examples of major forest engineering achievements of the last decade. Higher levels of automation including autonomous machine operation, and integration of intelligent and linked technology are examples of future directions. Conclusions: As with other disciplines, most Forest Engineering teaching, research or applications are multi-disciplinary. However, the review has highlighted specific achievements and future directions that helps define Forest Engineering as a unique discipline and one that can make a major contribution to the broader field of forest management practices.

Keywords: operations; education; research; technology

1. Introduction

Forest Engineering is a term and discipline commonly associated with the broader field of Forestry Science and forest operations, but a definition for Forest Engineering is often ambiguous and may not be interpreted as describing a unique discipline. At universities, Forest Engineering may refer to a separate program or qualification, or it may be used to place an operational emphasis within a broader program. In the industry practice, Forest Engineering can refer to a relatively unique set of activities, sometimes limited to just infrastructure development and equipment design, or can expand to include harvesting, safety and environmental management. In some regions of the world a Forest Engineer is a uniquely qualified and certified individual that has legal status for planning and oversight requirements.

There are 500 Forestry University and Colleges in the world [1], offering higher education to prospective forest managers. Although environmental subjects seem to have been the main focus for most such institutions in the recent past [2], forest operations are often part of the curricula and several of these institutions offer dedicated Forest Engineering degree programs. In essence, a Forest

Engineering degree can be pursued with two different approaches: In some universities (e.g., Oregon State University in the USA, University of British Columbia in Canada, University of Canterbury in New Zealand, etc.). Forest Engineering students are first and foremost educated within the engineering discipline, and then receive Forest Engineering specific course material to distinguish them from Civil or Mechanical Engineers [3]; elsewhere, Forest Engineering programs are based on a core Forest Science curriculum, reinforced in its the operational components, such as survey, harvest planning, roadbuilding and harvesting system selection.

While over 100 journals are identified as being forestry specific [4], at the international level, three scientific journals are specifically devoted to the discipline of forest engineering and publish high-quality peer-review papers in English. These are: The Croatian Journal of Forest Engineering, the European Journal of Forest Engineering and the International Journal of Forest Engineering. Furthermore, forest engineering papers are published in many other journals that deal with a number of different subjects, including forestry, agricultural engineering and energy.

Forest Engineering is also the focus of at least three regular international scientific conferences: Forestry Mechanization (FORMEC), held every year in Europe: Council on Forest Engineering (COFE) held every year in the US; Forest Engineering Conference (FEC) held every three or four years on a rotating seat throughout the world. In fact, FORMEC and COFE will join forces in 2019 and 2020 to combine their annual conferences in order to increase their respective networks and impacts, which represents an important step towards establishing a global platform for collaboration. At the same time, the International Union of Forest Research Organization (IUFRO) already offers a global meeting place with its group devoted to Forest Engineering subjects (Division 3), which has the purpose of strengthening research, fostering strategic cooperation, and promoting communication with non-Forest Engineering specialists [5].

All the above points at the existence of some general agreement about the importance of Forest Engineering, along with a strong local diversification. This should be regarded more as an opportunity than an obstacle to communication. Furthermore, forest engineering is inherently diverse as a discipline as it does not just comprise Engineering and Forestry subjects, but also requires a comprehensive knowledge of such matters as ecology, environmental impacts, occupational safety and health, and management. Researchers and practitioners from those disciplines are working closely with forest engineers to address a wide range of topics in today's forest management. The importance of such complexity and collaboration is indirectly demonstrated by the existence of several Forest Engineering glossaries, both printed [6,7] and on-line [8].

It has been noted that the recognition of Forest Engineering has declined over the past few decades, and this in turn has resulted in decreased funding and in a dwindling number of Forest Engineering graduates [5]. On the contrary, Forest Engineering specialists are increasingly demanded to accomplish various forest management objectives such as forest restoration and fuel reduction thinning operations, which are designed to improve forest ecosystem functions and reduce wildfire hazards.

The goal of this paper was to offer a contribution to help define the challenges and demands for forest engineering professionals and produce a set of definitions and terms related to Forest Engineering, offering them to the scientific community so that they can contribute to the basis for further debate. The paper also produced a summary list of the main achievements of Forest Engineering in promoting scientific and social progress in forestry, and in the human society at large. Finally, and as a logical consequence of analyzing past achievements, the authors also offered a condensed list of the most promising current research trends and future milestones.

2. Materials and Methods

Significant literature relevant to Forest Engineering and Operations was located using the "Google Scholar" search engine, along with the "Web of Science" and "Scopus" databases. Additional material was obtained directly from the authors' files and experiences, since all authors have a long-time experience with Forest Engineering. A literature synthesis method was used for organizing, categorizing and interpreting the results of the search, eventually leading to the present review papers, which summarize the extensive discussions conducted within the author panel. As a consequence, the criteria use for this review are strongly subjective, and reflect one of the many possible interpretations of the available material: That of the authors.

No structured quantitative method was used for analyzing the literature data and the authors acknowledge upfront the subjective perspective of this review, which is consistent with the stated goals of the paper. The authors never aspired to provide the ultimate definitions and achievement list in Forest Engineering and operations: They rather tried to offer a tentative reference to the scientific community that may serve as a basis for further discussion. Based on the literature and essential information extracted, this was organized into a logical framework to produce a narrative that should be useful to practitioners and scholars alike. Addressing such a wide audience is the main reason why the authors endeavored to draft an agile text and refrained from a more scholarly paper structure. At this point, the authors also want to apologize for the many inevitable omissions, which are not meant to downplay the valuable work of many of their esteemed colleagues. It is simply the result of a very rich production that can, contrary to a decline experienced in the recent past, show that interest in Forest Engineering is alive and well.

3. Definitions

Forest Engineering has been variably defined, but the most consistent definition and the one obtaining the largest agreement states that "forest engineering is the application of engineering principles and techniques to the management of forest lands" [9]. This includes working to ensure the health and sustainability of wildlands, timberlands and watersheds while allowing for such economic activities as timber harvesting and recreational use. For instance, the University of Canterbury Forest Engineering program defines the discipline as a hybrid of engineering, forestry and management science. Forest engineers are then professionals who can combine skills to solve engineering problems in the natural environment, with a focus on balancing societal, environmental and economic requirements [10]. Engineering programs in most western Countries are certified by the Washington Accord signed in 1989 that recognizes and accepts the engineer qualification from member countries and allows them to practice as certified engineers [11].

Another definition used in the past states that "Forest engineering includes all the management and administration activities that are necessary to transfer the standing tree into a product that is suitable for further processing or woodworking [12]. This definition also reflects forest engineering values, but in its form may engender some confusion with the term Forest Operations, which is often used interchangeably with Forest Engineering [13]. However, the two are not synonyms, as Forest Operations is just one component of Forestry Science programs and includes such elements as: harvesting system evaluation (including productivity and costing), infrastructure planning and construction (roading, surveying, stream crossings, etc.) and harvest planning/layout, including fieldwork, mapping and the application of geospatial technologies. Such operational aspects must be balanced with consideration of the environment, such as minimising erosion, and watershed protection through the implementation of Best Management Practices (BMPs) and certification programs, as well as safety and ergonomics.

Most Forest Engineering specific degrees have a range of topics but typically include forest management, wood science, soils (geotechnical), spatial technologies such as GPS, GIS, spatial analyses and optimization, natural resource utilization and ecology, economics and finance. This shows the strong overlap with Forestry Science programs. Visser [3] suggested there was a large range of Forest Engineering specific topics, including:

- Mechanics of Machines (design, improvements, attachments)
- Harvesting Systems (options, evaluation, costing)
- Operational Management (system design, time studies and evaluation concepts)
- Strategic, Tactical and Operational Harvest Planning

- Surveying (boundaries, roads, stands, buildings, etc.)
- Forest Roads/Infra-Structure Design (roads, bridges specifications, costs)
- Transportation (logistics, networks, optimization)
- Operational Impacts (stand damage, regeneration impacts)
- Value Recovery (wood quality, conversion, optimization)
- Forest Certification (SFI, FSC, ISO, etc.)
- Bio-energy (biomass production, storage, conversion)
- International Forestry (practices in other countries, comparisons)
- Forest watershed management (cumulative impacts, rivers, stream crossings)
- People/workforce management (safety, ergonomics, safety systems)
- Applications of new technologies (data capture integration)

Industry definitions can also shed light on the role of the Forest Engineer. As commercial forestry developed in the 1800s in North America, the 'Forest Engineer' was typically the person in charge of all engineering and operational aspects within a forestry company—a quite senior position. Duties could include designing and laying out roads and or railroad networks, supervising the construction of bridges and buildings, earth work projects including development of quarries, surveying land boundaries, as well as modification of mechanized equipment to serve in the rugged forest environment. Quite unique to the Pacific Northwest, Forest Engineers are certified through State entities and their oversight and signature is required for major infrastructure and harvest plans/harvesting operations.

4. Progress in Forest Engineering

Like most other disciplines, forest engineering has evolved over time in order to incorporate new knowledge and methods as they became available. Forest Engineering began integrating other disciplines as attention was set on additional subjects besides technology and economics. This progress has been conceptualized in many different ways, increasingly inclusive of many disciplines. In particular, one can describe this process as based on an enlargement of the original focus of Forest Engineering, or on a growing integration of other disciplines together with Forestry and Engineering. These are two ways to look at the evolution of the discipline and they both suffer from excessive simplification, once we recognize that reality is indeed complex. In fact, both "theories" basically describe a path that moves towards increasing complexity and integration, in recognition of such basic notion that can be expressed in at least two ways, as follows.

4.1. Paradigm Shift View in Forest Engineering

Heinimann [5] described the evolution of Forest Engineering as a series of paradigm shifts, leading to increased complexity as a result of the evolving notion of science, together with the emergence of new needs and the availability of better tools. According to him, four main general approaches have developed within modern Forest Engineering starting at the beginning of the 20th century. From an original Tayloristic approach aimed at increasing human productivity (Tayloristic paradigm), the focus of Forest Engineering shifted towards mechanization after World War II, when machines became commonplace in agriculture and forestry (Mechanization paradigm). Then, in the 1970s the attention moved from single machines to whole systems, expanding into a wider strategic view that had to cope with the complexity of real-world scenarios (System paradigm). This may have acted as a general warm-up for what was to follow, namely: The latest shift to the network paradigm [5]. This change occurred in the late 1990s, favoured by the widespread availability of powerful and affordable computers. Since then, Forest Engineering has followed the developments of intelligent technology, which is shaping the way in which we all think and work, in all disciplines and domains of life.

In short, the paradigm shift theory presumes a technology-driven evolution that has expanded the focus of our discipline from the detail to the whole, as soon as new and more powerful instruments became available to the scientists (and to the operator on the ground). Of course, the role of technology in this evolutionary path may have not been that of a mere physical enabler but must have resonated through the new ideas prompted by the technology development.

Shifting to a new paradigm does not mean that all other approaches are phased out: They remain useful and therefore they are maintained. The new approach simply represents an increment, not a replacement. As a result, the toolbox of the modern forest engineer still includes many and valuable techniques that follow more or less the same Tayloristic approach dating back to the early 1900s, such as time and motion studies, with good results [14].

4.2. Disciplinary Integration to Adapt to the Changing Needs and Views

Another way to look at the evolution of Forest Engineering considers the growing integration of other disciplines besides Forestry and Engineering. This runs alongside the paradigm shift theory, because the new disciplines co-opted within the realm of Forest Engineering generally reflect its shifting focus. The Tayloristic approach, for instance, has an ultimate economic goal [15,16], which has led to the early integration of Economics within Forest Engineering [17].

Later on, and along with the Mechanization and System approaches, came the integration of Ergonomics, Medicine, Psychology and Social Sciences, which were necessary to explore the human-machine interface and solve the new problems derived from increased mechanization of all forest operations.

More recently, the focus on networks and the widespread availability of information technology (IT) has generated new interests and created additional opportunities. Hence, the growing integration with new branches of Economics and Engineering, including Management and Programming. This perspective is reflected on new techniques when it comes to Forest Engineering science, especially for what concerns sensors and data processing. While retaining their crucial role, conventional statistics are increasingly bolstered by new analytical techniques better suited to reflect the complexity of the systems under investigation. As interest expanded beyond the productivity and cost of a single machine or team, so did the toolbox of the Forest Engineer, which has led to the widespread use of multi-criteria approaches, including Life Cycle Analysis (LCA) [18], sustainability impact assessment [19,20] and multi-criteria analysis [21]. As they reflect the complexity of strategic issues, the insights obtained with these methods are of specific interest to policy-makers, which illustrates a steady shift in terms of intended users.

Overall, these few examples show that Forest Engineering evolved over time, and that this evolution concerned the focus, the methods and the intended users. As they look at one dimension only, all different theories are partial by definition. Suffice to say that over a century, Forest Engineering has proved capable of adapting to the changing needs and views of our society, and as such is a living component of its culture, albeit small.

5. Main Achievements and Future Directions

Placed right within the Network Paradigm period, the past decade has seen many important developments to benefit a rapidly evolving industry that sets the demands for new tools and knowledge. Therefore, one way to structure a summary description of these developments is to start from the main new trends in the forest industry, such as:

- the ever-increasing mechanization, aimed at reducing direct human input and exposure
- the growth of the bio-economy, with its demand for innovative bio-based products
- the “Internet of things”, which prefigures a connected world, where large volumes of data are made available and exchanged within and between networks in real time.

5.1. Increased Mechanization

Incremental improvements are continuously being made to existing forestry machines. Embedded electronics (e.g., sensors, measuring tools, video feeds) are commonplace and can help to automate specific functions such as processing stems to logs by moving the head to predetermined positions according to the log grade. The data captured during felling and processing can be augmented by geospatial information to analyse and optimise machine performance, as well as use this to implement the concept of precision forestry [22,23]. Another example of the software aiding machine control is the new John Deere 'Intelligent Boom Control' system that allows the operator to control the movement of the head directly, as opposed to moving each individual component of the boom. It has already been shown that the use of such technology makes it easier to learn to operate harvester or forwarder machines and to achieve sustained productivity within a shorter learning time [24,25]. Komatsu recently published a vision of using drones, including communication technologies and cloud services to improve harvesting efficiency.

Information on robotics in forest operations is primarily found in the 'grey literature', i.e., websites [26]. However, examples of journal articles start in the late 1980s with Courteau [27] providing an overview of developments of robotics in forestry. Guimier [28] concluded that a new technology in machines would be equipped with 'intelligent' control systems that allow them adapt to their working environment. Thor noted that mechanised systems would continue to be automated until robots could be used for harvesting operations [29]. More advanced concepts are presented for specific elements, such as development of unmanned forwarders [30] or summary papers that investigated a range of robotic options [31,32].

Successful implementation of autonomous equipment will be driven by their productivity and operational cost [33,34]. Given that labour is typically about 30% of operating costs [31], an autonomous machine can be less productive but still be more cost effective [35]. However, there are other factors to consider; a study by McEwan [36] highlighted the consideration of additional benefits relating to health and safety, environment, quality (in terms of increasing value or reducing waste), but also social aspects [37]. While modern machines are well designed with regard to ergonomics, this has led to many operators working longer hours per day [38] and has created different health risks to the traditional manual physical risks. For example, harvester operators can quickly fatigue, or a forwarder operator might spend many hours a day traversing the same trails, which can lead to monotony. A higher degree of machine autonomy could readily decrease these types of occupational health and safety risks.

5.2. Biomass for the Bioeconomy

Forest management activities, including timber harvesting and fuel reduction thinning treatments, generate forest residues, such as branches, chunks, and small-diameter trees (referred to as biomass hereafter). While limited in other uses, this woody biomass is a good source for energy production. The energy that is produced from the woody biomass in the form of electricity, heat, or a combination of both is considered "renewable", as trees re-grow after forest harvesting [39]. Each year, there are 103 million bone dry tons (BDT) of biomass that are available to harvest sustainably in the United States, if markets pay $60 per BDT [40]. As the market value of this biomass increases, the more it becomes economical to recover. Similarly, large amounts are available in Europe and in the other continents [41].

Utilizing biomass is an ideal option for not only the production of renewable energy, but also for the disposal of forest residues that would otherwise hinder the growth of new trees or need to be removed via more harmful methods (i.e., open-air burning). Forest engineering and operations, therefore, are central to both biomass energy and forest management. In recent years, this sector has become increasingly advanced in its systems and technologies for harvesting and transportation, while addressing key issues in forest residue disposal.

The role of forest engineers in biomass utilization is to supply biomass feedstock, for example in the form of wood chips or hog fuel. When working with forest residues that are typically mixed with variable material sizes and types, forest engineers have put considerable effort into selecting the right machines and analyzing logistics and transportation efficiency to deliver the highest quality biomass feedstock at the lowest cost, year-round [42–44]. They must use this expertise to design systems that are tailored to the region in which they are operating. For example, the system based on a feller-buncher, skidder, and loader is commonly used to harvest energy wood in forested areas in the southeastern region of the United States [45]. In the western United States, a centralized forest residue recovery operation consisting of a grinder/loader, off-road trucks/loader, and chip vans is routinely implemented [46,47]. Furthermore, forest engineers must also designate optimal landing locations along with efficient skidding trails that are linked to well-developed forest roads to effectively manage biomass operations. In short, a wide range of variation in biomass harvesting systems has been developed to address an equally wide range of unique operations conditions, such as steep slopes and long distance to markets. In Europe, the dominance of cut-to-length harvesting technologies require different recovery methods and an equally accurate knowledge of the capabilities of the equipment at hand, and of the specific characteristics of the sites [36].

In recent years, researchers and engineers have strived to design systems that will deliver biomass feedstock that are compatible with specific biomass conversion technologies, such as torrefaction, gasification, and pyrolysis [48,49]. While these newer technologies create exciting opportunities for utilizing forest residues and small-diameter trees that might otherwise go to waste, they present a challenge: Each biomass conversion technology requires narrow feedstock specifications for efficient operation. For example, a mobile torrefaction system requires wood chips that are 0.5 mm−2 cm in length, relatively dry (<20% moisture content), and works with high (>15%) ash content materials [50]. To meet those feedstock specification requirements, forest engineers have been working with companies that manufacture chipping and grinding machines to produce smaller wood chips with lower moisture and ash contents. Producing micro- chips [51,52] and sawdust [53], separating stem-wood from forest residues [54], and screening feedstock materials [55–57] are just some of the strategies that can be used to produce feedstock that are uniform in size and low in moisture and ash contents, and therefore compatible for these novel biomass technologies.

From a forest management perspective, forest residue removal/utilization is more important than the production of energy. The mechanical removal of forest residues effectively facilitates the process of tree planting on harvesting sites, minimizes forest fire hazard, reduces habitats for harmful and invasive insects, and improves the aesthetic value of forests [58]. For example, mechanical removal and utilization of forest residue piles on the timber harvesting sites can potentially reduce the cost of slash disposal at an amount of around $1000/ha [54] and it will speed up the planting work. These piles do not decompose for an extended time period (>30 years) [59], posing fire risks, providing habitats for insects [60], and negatively impacting the timberland's aesthetic values. A common method of addressing these issues is pile burning or prescribed burning, but this method is deleterious to air quality, costly to implement, and limited to the window of the burning season [61]. Therefore, the mechanical removal of forest residues is the ideal option for forestland managers. In this way, forest operations that harvest and process residues into biomass feedstock not only fulfills the needs of energy production but addresses other significant concerns and issues in today's forestry.

5.3. IT Technology and the Internet of Things

With the Internet of Things (IOT) any number of agents—machines, humans and objects—are uniquely identified and are remotely connected within the same network in order to automatically exchange information [62]. This fits very well within the current network paradigm and opens a wealth of possibilities [5].

In everyday practice, machine connectivity is used for operational management, through the remote collection of machine status and production data [63,64]. The availability of these data allows monitoring and improving machine performance, planning machine maintenance and often executing maintenance interventions when issues arise with on-board electronics. Similarly, production instructions can be sent directly to the machines in real time, so as to maximize production flexibility. Remote machine monitoring was explored already many years ago—more than a decade in Northern Europe, for instance—but it is now quite common with modern forest machines used worldwide. In fact, the use of smart phones now allows real-time communication and the automatic collection of production data from manual operations, as well [65].

A more recent example, and something that promises to become generalized in the near future, is the introduction of augmented reality, whereby several data streams are combined and fed to machine operators so as to facilitate their tasks [66]. In Forest Engineering the use of augmented reality is at an experimental stage on a number of different devices and is most often integrated with visualization tools that feed additional information otherwise unavailable. That is the case of tree quality information appearing on the screen when an operator selects a tree for cutting, or of an operator being fed repeat visualizations of the same object in front of them, each taken from a different angle, so that they can better evaluate spatial conditions. In the US, the application of tablet technology in forest operations is gaining a strong interest, allowing feller-buncher and harvester operators to make their felling decisions without painting trees to cut or leave. The progress of in-woods operations is reported to the office through the combination of a computer system installed on the machine and GPS technologies, so that operational work plans can be updated on a real time basis.

Finally, the biggest opportunity lays with the large amount of production data now available for customized processing, which can be used for many purposes besides the monitoring of an individual machine. In particular, these data can be used to maximize the technical, economic and allocative efficiency of any single team or fleet. The on-board computers of modern machines deliver a constant stream of extremely valuable information, which can be combined with remote sensing data and market information for additional impact [67]. Whether they are combined or not, these data sets are too large for traditional processing applications, and configure as Big Data [68], which is considered as one of the main opportunities for innovation and efficiency gains over the future [69]. Today 50% of internet traffic is not generated by human input, but directly by machines that connect to each other. Similarly, the number of devices connected globally now exceeds 30 billion—that is, six times the number of humans [70]. Machines therefore talk to each other, and connectivity is and will increasingly be a fundamental element in production efficiency. Machine generated data can be used with profit by everyone, from the large company to the single contractor. A typical use is that of monitoring the productivity of all the elements in a fleet and matching that of each against benchmarks extracted from the fleet as a whole. Once this data is available, moving benchmarks can be estimated with suitable statistical techniques, such as the Data Envelopment analysis or Stochastic Frontier Analysis [71,72]. On-line platforms are already available for the purpose, which have been developed by the individual companies, contractors' associations and public agencies [73,74].

The ability to generate and manage real-time data is also critical in the field of certification and training: Automatic data collection is often combined with the Chainblock technology to produce indelible records, and constitutes the basis of a large number of apps used by certification agencies that work with sustainable forest management as well as logger training [75].

6. Conclusions

Forest Engineering must be recognized, defined, and better understood as a unique discipline. Today's forest management practices demand a broader application of Forest Engineering within the interdisciplinary context of forestry. Key accomplishments in and the future direction of Forest Engineering include increased mechanization, contributions to bioenergy and biomass economy, and real-time decision-making and optimization using IT and internet applications. In particular, Forest Engineering is a remarkably adaptable discipline that has expanded its toolbox to match the changing needs of human society. As a result, Forestry Engineering can be defined in different ways according to context. Due to the strong association with forestry and forest management, the role of Forest Engineering may change with that of forest management. In that regard, one may make a critical distinction between industrial plantation forestry and conventional forestry. Since the primary goal of most industrial plantation forests is fiber production, the demands made on Forest Engineering are still largely technical and economical and place a great emphasis on the more traditional components of the discipline as exemplified in the Tayloristic and Mechanization paradigms. On the other hand, conventional forestry is taking up a variety of roles besides fiber production. The additional demands made on conventional forestry range from soil protection to biodiversity and recreation and require forest engineers to expand their competence beyond purely technical and economical matters. That is a strong driver of future developments, possibly leading to the evolution of Forest Engineering into an increasingly complex discipline. Within such context, this manuscript aims at defining the unique identity of Forest Engineering, while providing thoughts and ideas for further discussion. To accomplish these goals, the authors reviewed and synthesized literature covering academic, research, and industry practice. Hopefully, this study offers at least a glimpse of the pivotal achievements of Forest Engineering from the last decade and identifies some of the major issues that can be addressed only through the effective use of Forest Engineering in the near future.

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