COMMUNAUTÉ FRANÇAISE DE BELGIQUE

UNIVERSITÉ DE LIÈGE – GEMBLOUX AGRO-BIO TECH

Dealing with storm impacts on the forest sector through integrated and systemic approaches at the regional level

Simon RIGUELLE

Essai présenté en vue de l'obtention du grade

de docteur en sciences agronomiques et ingénierie biologique

Promoteurs : Dr. Benoit JOUREZ

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Summary

RIGUELLE Simon (2016) Dealing with storm impacts on the forest sector through integrated and systemic approaches at the regional level (PhD Thesis). University of Liege – Gembloux Agro-Bio Tech, Belgium, 173 p.

Wind is one the most damaging natural hazard that forests are facing worldwide and in Europe. Destructive storms lead to severe forest damage and consequently cause disruptions in daily forest management and timber supply chains. Major dysfunctions can happen at each step of forest-wood chains and at each level of management, leading to huge economic losses and long-lasting crises within public organisations and private companies. In this context, the first part of this work aims at handling those complex and multi-facetted storm-related issues with new approaches in order to mitigate economic, environmental and societal impacts of storms on the forest-based sector. In a first step, an overview of risk management practices in forestry is presented, as well as major determinants of storm damage risk management. SWOT analyses are also used for highlighting main issues and opportunities in current windthrow management process. In a second step, an integrated framework is proposed for tackling those strategic issues and seizing opportunities arising from the uncertain decision-making context. A systemic perspective is also presented for managing storm damage risk at regional, national or supranational level with a holistic perspective. In regards to those original approaches, the thesis also highlights some of the crucial challenges public authorities might address for enhancing their affectivity in this process. In the second part of the manuscript, three particular aspects of storm damage management are considered: contingency planning, the development of decision-supporting tools for the forest community, and timber storage planning at the regional level. Those topics are illustrated by case studies taking place in Wallonia, Belgium. In particular, the development of a model-based decision support system (DSS) illustrate how systemic analysis can help on the one hand designing balanced strategies for the regional forest-based sector in case of severe wind damage and on the other hand identifying bottlenecks that should be solved before the next huge storm to enhance systemic resilience and resistance. Regarding timber conservation, a GIS-based methodology for locating optimal areas for sprinkling storage at the regional scale is presented, together with an applied study on the influence of anaerobic storage process on the quality of spruce logs. From a wider perspective, this thesis reveals that taking decision under uncertainty will remain a key challenge to address in forestry, especially in the context of climatic change. However, original methodologies focusing on systemic and integrated risk management approaches can help in this effort. Finally, the work emphasises the urgent need of effective risk management policies at regional, national, and international levels to guide researchers, forest managers and industrials.

Résumé

RIGUELLE Simon (2016) Gestion des conséquences des tempêtes sur la forêt et la filière bois au travers d'approches systémiques et intégrées (thèse de doctorat). Université de Liège – Gembloux Agro-Bio Tech, Belgium, 173 p.

Les tempêtes sont l'un des phénomènes naturels les plus dommageables auxquels les forêts sont confrontées dans le monde et en Europe. Les violentes tempêtes hivernales peuvent conduire à de graves dommages pour la ressource forestière et par ricochet provoquer des perturbations dans la gestion durable des forêts et dans l'approvisionnement à moyen et long terme de la filière bois. Les impacts directs et indirects des tempêtes peuvent conduire à d'énormes pertes économiques et à des situations humaines difficiles, tant pour les propriétaires que pour les gestionnaires publics et privés. Dans ce contexte, cette recherche a pour objectif de développer des outils et des procédures afin de prendre en considération les enjeux complexes et multidimensionnels associés au risque de tempêtes, et ce dans le but d'en atténuer les impacts économiques, environnementaux et sociétaux sur le secteur forestier. Le premier volet de ce travail vise à questionner et repenser la gestion de ces phénomènes au travers du filtre de nouvelles approches intégrées et systémiques. Dans une première étape, un aperçu des pratiques classiques de gestion du risque dans le secteur forestier est présenté, ainsi que les principaux déterminants de la gestion des dégâts de tempête. Des analyses AFOM (Atouts-Faiblesses-Opportunités-Menaces) ont été utilisées pour mettre en évidence les principales difficultés et opportunités émergeant du processus actuel de gestion des chablis. Dans une deuxième étape, un cadre intégré est proposé afin de traiter ces questions stratégiques et saisir les opportunités découlant de la prise de décision en contexte incertain. Une approche systémique est également proposée pour la gestion des risques au niveau régional, national ou supranational. La thèse met également en évidence les principaux défis que les pouvoirs publics devraient relever pour améliorer leur affectivité dans ce processus. Dans la seconde partie du manuscrit, trois aspects particuliers de la gestion des crises résultant des dégâts de tempête sont développés plus en détail: la planification d'urgence, le développement d'outils d’aide à la décision et la planification stratégique et opérationnelle du stockage du bois chablis à un niveau régional. Ces sujets sont illustrés par des exemples issus de la forêt wallonne, en Belgique. En particulier, le développement d'un système d'aide à la décision basé sur la modélisation de la filière bois illustre comment l'analyse systémique peut aider, d'une part, à la conception de stratégies équilibrées pour la filière forêt-bois régionale en cas de graves dommages forestiers, et, d'autre part, à identifier les goulots d'étranglement qui devraient être réglés avant la prochaine tempête pour améliorer la résilience et la résistance de la filière. En ce qui concerne les aspects opérationnels de la gestion de crise, une méthodologie est proposée pour localiser les zones optimales de stockage par aspersion à l'échelle régionale. En outre, les résultats d'une étude portant sur l'influence du stockage par voie anaérobie sur la qualité du bois d’épicéa sont présentés. Du point de vue général, cette thèse a mis en lumière que la prise de décision dans l'incertitude demeure un défi majeur pour la communauté forestière, en particulier dans le contexte du changement climatique global. Cependant, des approches systémiques et intégrées de gestion des risques, inscrites dans le cadre d’une réelle gouvernance des risques forestiers, peuvent contribuer à réduire ces incertitudes et à guider les chercheurs, les gestionnaires forestiers et les industriels. Pour terminer, la thèse met l'accent sur l’importance de la communication avec les acteurs et la prise en compte de leurs attentes.

“Tous les autres phénomènes que les mortels voient s'accomplir sur terre et dans le ciel tiennent leurs esprits suspendus d'effroi, les livrent humiliés à la terreur des dieux, les courbent, les écrasent contre terre ; c'est que l'ignorance des causes les oblige à abandonner toutes choses à l'autorité divine, reine du monde ; et tout ce qui leur dérobe ces causes, ils le mettent au compte d'une puissance surnaturelle”

Lucrèce

“Predicting the future accurately is not so important, being ready for it is”

Pericles

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Comme l'a si bien dit H.C. Andersen, la reconnaissance est la mémoire du cœur. De la reconnaissance, je ne saurais que trop en exprimer à toutes les personnes qui ont permis que ce projet éclose, prenne racine, croisse, et aboutisse. Il en va en effet d'un projet de thèse un peu comme d'une jeune pousse de chêne, qu'il faut initier et éduquer pour qu'elle rejoigne, un jour peut-être, le haut de la futaie.

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Pour terminer, je délaisserai la métaphore du chêne et ferai mienne celle du roseau, lui qui plie mais ne pas rompt pas sous les bourrasques. Pour ce faire, pour résister au découragement, j'ai pu compter sur le soutien inconditionnel de Pascale, encore plus dans les périodes de doute où l'abandon guette. Tel un *phare dans la tempête*, elle m'a permis de garder espoir et d'atteindre cet objectif à la fois professionnel et personnel. Pour cela et tant d'autres choses, merci de tout cœur.

Publications

Publications in peer-reviewed journals:

- RIGUELLE, S., HÉBERT, J. & JOUREZ, B. (2016). Integrated and systemic management of storm damage by the forest-based sector and the public authorities. *Annals of Forest Science*, 73, 585-600. URL - Orbi
- RIGUELLE, S., LESIRE, C., HÉBERT, J. & JOUREZ, B. (2016). Influence of a long-term storage in anaerobic conditions on Norway spruce (Picea abies, L. Karst.) physical and mechanical wood properties. *Wood Material Science & Engineering.* URL - Orbi
- RIGUELLE, S., HÉBERT, J. & JOUREZ, B. (2015). WIND-STORM: A decision support system for the strategic management of windthrow crises by the forest community. *Forests,* 6**,** 3412-3432. URL - Orbi
- RIGUELLE, S., HÉBERT, J. & JOUREZ, B. (2009). Un outil d'aide à la décision pour la gestion des chablis en Région wallonne. *Innovations Agronomiques,* 6**,** 113-123. URL - Orbi
- RIGUELLE, S., JOUREZ, B., HÉBERT, J., PIROTHON, B. & LEJEUNE, P. (submitted: 23.05.16 / accepted with major revisions: 23.08.16). A GIS-based decision-support system for locating sprinkling storage terminals for windblown timber. *Biotechnology, Agronomy, Society and Environment.*

Other publications:

- RIGUELLE, S., LESIRE, C., HÉBERT, J. & JOUREZ, B. (2015). Etude de la qualité du bois d'épicéa conservé sous bâches hermétiques. *Forêt Nature,* 137**,** 61-67. URL - Orbi
- RIGUELLE, S., HÉBERT, J., JOUREZ, B. & ROMMELAERE, A. (2011). Le plan chablis : un outil de planification d'urgence et de gestion de crise pour la forêt wallonne. *Forêt Wallonne,* 111**,** 3-9. URL - Orbi
- RIGUELLE, S. (2010). Plan chablis - Guide pour la gestion des crises chablis en Wallonie. Jambes: Service public de Wallonie.
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Notes: The content of above papers included in this manuscript has been transcribed without any changes. However, some editing changes have been applied. Bibliographic styles have been harmonized into a unique format (*Harvard*) as well as the language (*British English*). References cited in each publication are all listed together with those cited in chapters 1, 2, 4, and 8 at the end of the manuscript. Papers specific mentions (authors' affiliations, acknowledgments or conflicts of interest) are not included in this manuscript. Figures and Tables are numbered in a continuous order.

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General introduction

Wind is among the most damaging natural hazards that forests are facing in Europe (Munich Re, 2002, Hanewinkel et al., 2011, Fares et al., 2015). Compared to other common biotic and abiotic hazards (drought, snow, fire, pest outbreaks), wind has been responsible for more than half of forest damage – more than two billion cubic meters – in Western Europe over the period 1950-2000 (Schelhaas et al., 2003). Since three decades, European forest sector was toughly affected by several huge storms, especially in 1987, 1990, 1999, 2005, 2007 and 2009 (see e.g. Grayson, 1989, Bründl and Rickli, 2002, Peyron, 2002, Schindler et al., 2009, Valinger et al., 2014). Worldwide, wind calamities are also major threats for regions concerned by extensive forest production and integrated forest-based economies, for example in Northern America (Dale et al., 2001, Elie and Ruel, 2005), Japan (Kamimura and Shiraishi, 2007) or New-Zealand (Moore and Somerville, 1998).

This thesis addresses the management of destructive storm events, leading to severe forest damage and causing disruptions in daily forest management and timber supply chains. After a destructive storm, major dysfunctions can happen at each step of forest-wood chains and at each level of management (strategic, tactical and operational) and often result in long-lasting crises within public organisations and private companies. On the contrary, this work does not address most frequent but less impacting windy events that do not reach critical thresholds. Sometimes considered as *endemic* storm damage (Pasztor et al., 2015), damage caused by these kind of events do not cause timber market failures at regional scale, whereas it can affects severely local forest owners. For a long time, windthrow management was mostly considered from an economic perspective (Holmes et al., 2008). Indeed, a storm that blew down at least the equivalent of an annual average harvest at the industrial supply scale mainly affects timber production and prices (Brunette et al., 2012). Since forest owners are tempted to harvest to limit financial losses, the afflux of timber on the market combined with a poorer quality of fallen timber and the increasing costs of salvaging contribute to lower stumpage prices for forest owners (Prestemon and Holmes, 2004). The latest are also suffering from future revenue losses due to an anticipated harvest of non-mature stands (Nieuwenhuis and O'Connor, 2001b). The industry as a whole is also affected by the short-term increase in the wood supply after the storm, usually followed in the medium term by a supply shortage if no mitigation measures are taken (Schwarzbauer and Rauch, 2013). A storm event will also cause operational difficulties resulting from the lack of harvesting and transport capacities that may slow windfall mobilization and storage operations.

However, through the years, societal and environmental concerns have arisen in the storm damage management process. From an environmental perspective for instance, wind disturbances may cause a huge reduction of forest carbon sinks (Lindroth et al., 2009) and threaten the delivery of forest's goods and services in damaged areas (Lindner et al., 2010). In addition, the society is also affected by storms' consequences, i.e. occurrence of civil casualties, alteration of landscapes, and of living conditions (Blennow and Persson, 2013). Nowadays, sustainable forest management (SFM) concept also questions the role of forest ecosystems in regards to natural disturbances, whereas forests' multifunctionality is promoted in several national regulations. These new trends, combined with the emotional connections of people with woodlands and a stronger media pressure on public decision-makers, indubitably jeopardise the management of storm damage. Manifold responses were provided since a couple of years, however, regarding previous crises, one can wonder if those individual approaches are leading to cost-effective strategies at the aggregated level (i.e. regional or national level) and are optimizing the global welfare of the forest-based sector while integrating various stakeholders, interests and beliefs.

Starting from this statement, the **goal of this thesis** is thus to consider the storm damage management process through a new prism, in order to identify ways of improvement and provide a support to public and private decision-makers. For this purpose, we used a risk-based approach, in which the term *risk* embraces all uncertain outcomes of a destructive storm on each forest functions that are valuable by stakeholders. This research is also considering storm damage issue from a decision-making perspective. The underlying hypothesis is that public authorities (i.e. governments and public bodies) as well as private decision-makers are playing a crucial role throughout the risk management process and must therefore be at the centre of forthcoming storm damage mitigation strategies. The following manuscript is divided in three distinct parts, each of them being dedicated to a specific aspect of the storm damage risk management process.

The **first chapter** gives a general insight about analysis, perception, acceptability and communication of risk. Firstly, options to classify a risk are presented, as well as the main types of stakeholders involved in the process. Then, two main frameworks for analysing risks are described: the classical and the risk governance approach. Notions of risk assessment and management in relation with those frameworks are also introduced. Finally, we discussed how risks are perceived and accepted by people, and what should be the role of communication within the risk analysis process.

Figure 1. Wind damage in Schmallenberg (NRW, Germany), Storm Kyrill, January 2007

The **second chapter** begins with a description of the various impacts associated to destructive storms. Impacts of wind events on forest resources and consequently on the forest-based sector can be classified in different ways. However, impact-based classifications are often preferred to strictly meteorological definitions of damaging events because they reflect the interactions between the hazard (*wind*) and its target (*forest*). Indeed, the severity of damage results from a combination between the storm features and local factors such as the local wind-climate (Jung et al., 2016), site and soil conditions (Usbeck et al., 2010), trees and stands stability (Peltola et al., 2000, Nicoll et al., 2006) or previous silvicultural practices (Valinger and Fridman, 2011). Determinants of damage – hazard, vulnerability and exposure – and future trends associated to it are briefly presented in this chapter too. In a second step, an overview of environmental, economic and societal impacts of storms is done, highlighting the multidimensional feature of storm damage management. Then a short description of current risk assessment and management practises is presented. Since a storm cannot be avoided, storm damage management usually try on the one hand to foster adaptation of forest management to reduce the risk of damage and on the other hand to mitigate storm's consequences. The concept of systemic resilience is also discussed at this stage.

Starting from this overview on storm-related risks, an evaluation of current risk management approaches is done in the **third chapter**. For this purpose, a SWOT (Strengths – Weaknesses – Opportunities – Threats) methodology is used to identify drivers and barriers, either internal or external, concerning the strategic management of storm events by both forest-based actors and public authorities. Based on a thorough review of past crises and scientific literature, this analysis enables us to come with proposals on original framework and methodology to deal with storm damage in more integrated and systemic ways at the strategic level. This work is synthesized in the peer-reviewed paper n°1 (Riguelle et al., 2016b) which makes the body of this chapter.

In the second part of the manuscript, risk management and decision-making issues are addressed. The WIND-STORM software – peer-reviewed paper n°2 by Riguelle et al. (2015a) – is presented in the **fourth chapter**. This decision-support system (DSS) was built starting from the initial assumption that integrated and systemic management are likely to improve strategic decision-making at the regional level. Therefore, we used System Dynamics modelling concepts to develop the *Walloon Forest Model*, a regional model able to simulate timber supply chain functioning after the storm. This tool can be used, i.e. to compare crisis management scenarios and select most effective option for all stakeholders. Whereas DSS's settings are defined for the specific case study of Wallonia (Belgium), it can be adapted easily to other similar regions in Western Europe.

The **fifth chapter** tackles contingency planning and crisis management issues, which are among the major challenges public authorities are facing to reduce the global impact of destructive storms. The contingency plan (Riguelle, 2010, Riguelle et al., 2011) developed for the regional case study of Wallonia (Belgium) is presented to illustrate how public bodies can make use of those tools to improve preparedness and reactivity towards windthrow crises. This chapter also presents the damage assessment methodology and associated IT-tool that enables faster decision-making and emergency response by the public authorities.

The implementation of strategic decisions is the theme of the last section. The **sixth chapter** makes the link between strategic and operational management of windthrow crises. More particularly, we choose the timber storage issue, which appears to be one of the major bottlenecks in crisis management process, to illustrate how science can support decision-making at the tactical level. The output of this reflexion is a GIS-based DSS that could support public and private stakeholders in identifying optimal locations for water-storage terminals before and after the storm. According to a more technical perspective, we also consider in the **seventh chapter** the relevance of anaerobic storage as a complement to sprinkling storage for long-term storage of storm-damaged timber. For this purpose, mechanical and physical properties of Norway spruce logs (*Picea abies* L. *Karst*) were studied after a 4-year in-situ storage This final work was presented in the peer-reviewed paper n°4 (Riguelle et al., 2016b).

Finally, the general discussion gives us the opportunity to step back and discuss what are the main contributions and limitations of our work. We particularly discussed the human factor as a source of failure of such approach. Finally, four main challenges for the public authorities in Wallonia are presented, and priorities for the forest community in the upcoming years are drawn.

First section

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Dealing with storm damage risk: concepts and proposals

- This first section is dedicated to risk assessment and management concepts. Starting from the conceptual framework for risk analysis, we successively focused on storm related risks and their handling by public and private decision-makers.

- In the first part of this section - chapter 1 – the notion of risk is introduced and main approaches for analysing risks are presented. Risk perception and communication with stakeholders are also discussed.

- In the second chapter, we used an impact-based classification for drawing the main characteristics of risks associated to destructive storms. An overview of current knowledge is presented, as well as a reflexion about risk management in forestry under climatic uncertainty.

- The last part – chapter 3 – presents a risk governance approach for handling storm damage management issues. Strengths, weaknesses, opportunities and threats regarding storm damage management were analysed from both forest-based sector and public authorities' angles. Then integrated and systemic approaches are suggested to implement an *inclusive* governance of risks. Finally, recommendations are given to public authorities in order to improve their involvement in this process.

1

CONCEPTS ABOUT RISK

This chapter introduces the notion of risk. We found crucial to remind major concepts about analysis, perception, acceptability and communication of risk, because risk can be defined in many ways and handled through different methodologies. An application of these concepts to windthrow-related risks is presented in the next chapter.

1.1. DEFINITION

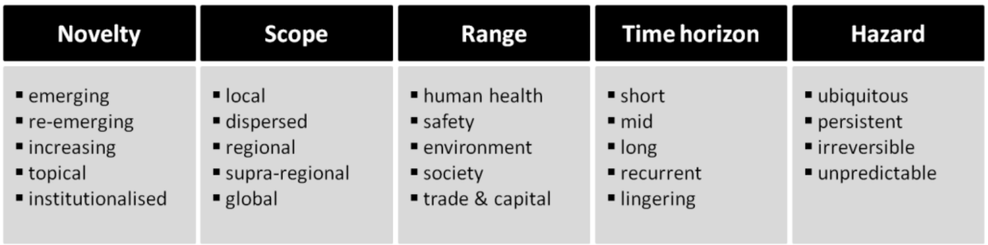
Risk is probably one of the most confusing words in the common language, and therefore there is no unique and agreed definition of it. Risk definitions can usually be grouped in two categories (Aven and Renn, 2010): in the first group, risk is expressed by means of probabilities and expected values ; in the second group, risk is expressed through the consequences of an event and associated uncertainties. In this thesis, the following definition, slightly adapted from Aven and Renn (2009), was chosen:

"Risk refers to uncertainty about and severity of an event and its consequences with respect to something that is valuable by humans".

This definition allows considering uncertainty as a determinant of the risk level, beside the expected outcomes (Kaplan and Garrick, 1981). The uncertainty relates to both the event (i.e. the windstorm) and the outcomes (i.e. the consequences of a storm on the forest-based sector). According to Aven and Renn (2010), severity embraces in this definition the intensity, size, extension, scope and other potential measures of magnitude, and relies to something that humans value (lives, money, etc). Losses and gains, for example expressed in monetary terms, are ways of defining the severity of the outcomes. However, there are damage whose valuation is difficult because they relate to social, cultural, environmental, or patrimonial fields (Birot and Gollier, 2001).

1.2. CLASSIFICATION

Risk is a multidimensional concept and is thus difficult to classify. One possible approach to classify the risk is to consider a number of dimensions which typically should influence the risk governance process (IRGC, 2007), as for instance the degree of novelty, the scope, the range, the time horizon, and the type of hazard involved (Figure 2). Other dimensions can relate to the available management options, values at stake (equity, social or business concerns, trade agreements), the regulatory framework, etc. (IRGC, 2007). In addition, one can highlight the appearance of a new type of risks that arise from the emergence of a “Risk Society”, as framed by Beck (1992). Those “reflexive” risks (Brunet, 2007), which are linked to the inherent functioning of our modern societies, often get out of classical risk analyses for several reasons (Brunet and Schiffino, 2012a).



Novelty	Scope	Range	Time horizon	Hazard
▪ emerging ▪ re-emerging ▪ increasing ▪ topical ▪ institutionalised	▪ local ▪ dispersed ▪ regional ▪ supra-regional ▪ global	▪ human health ▪ safety ▪ environment ▪ society ▪ trade & capital	▪ short ▪ mid ▪ long ▪ recurrent ▪ lingering	▪ ubiquitous ▪ persistent ▪ irreversible ▪ unpredictable

Figure 2. Possible approach to classify the risk

Another source of complexity is the diversity of potential stakeholders, who can be classified in three categories: the experts, the decision-makers and the citizens. External intangible players such as the media and the moral authorities are also interacting with them. Their relationships, or power games, can be illustrated by the concept of Machiavelli’s chessboard (Chevassus-au-Louis, 2007). In this depiction, decision-makers are at the centre of the chessboard, interacting with the experts, citizens, media and the moral authorities, which all expect to become deciders in turn (Figure 3). These players all bring their own expectations and values to decision-makers, who are supposed to find the right balance between these four sources in order to avoid abuses (technocracy, demagogy, media dictatorship, etc.). Among other consequences, these relationships among players involved in risk analysis highlight the fundamental importance of the communication strand during risk assessment and management phases.

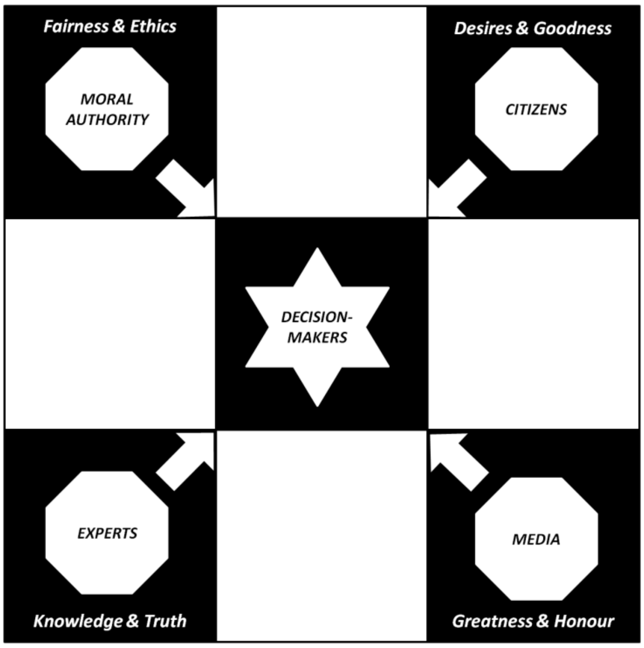


Figure 3. Relationships among players in risk analysis (adapted from Chevassus-au-Louis (2007))

While such multidimensional issues should implies an holistic management (Haimes, 2008), their complexity is often reduced, deliberately or not. For example, operational managers often tend to slice multidimensional issue into several one-dimensional issues in order to ease their management. On the other hand, close-minded or too sectoral risk analysis approaches can fail to catch the whole picture, giving the illusion of a simpler reality.

1.3. ANALYSIS

According to Chevassus-au-Louis (2007), a risk analysis process can be defined as all the successive processes ranging from the identification of a potential threat for the society (*risk assessment*) to the implementation of appropriate risk handling measures for this society (*risk management*). In this definition, the term “appropriate” means that those measures are suitable regarding the risk but also assimilated by the society (Chevassus-au-Louis, 2007). There are two main ways for dealing with risk analysis: the classical or the risk governance approach.

1.3.1. Classical approach

Under the classical – or *modern* – approach, risk analysis can be view as a linear and iterative process that aims at assessing, managing and communicating about the risks in order to minimize their adverse effects (Figure 4). In this approach, the evaluation of risks is mainly quantitative and is only based on experts' knowledge and scientific evidences. In order to assess a risk, one can follow the logic introduced by the set of triplets presented by Kaplan and Garrick (1981):

- What can go wrong?
- What is the likelihood that it would go wrong?
- What are the consequences?

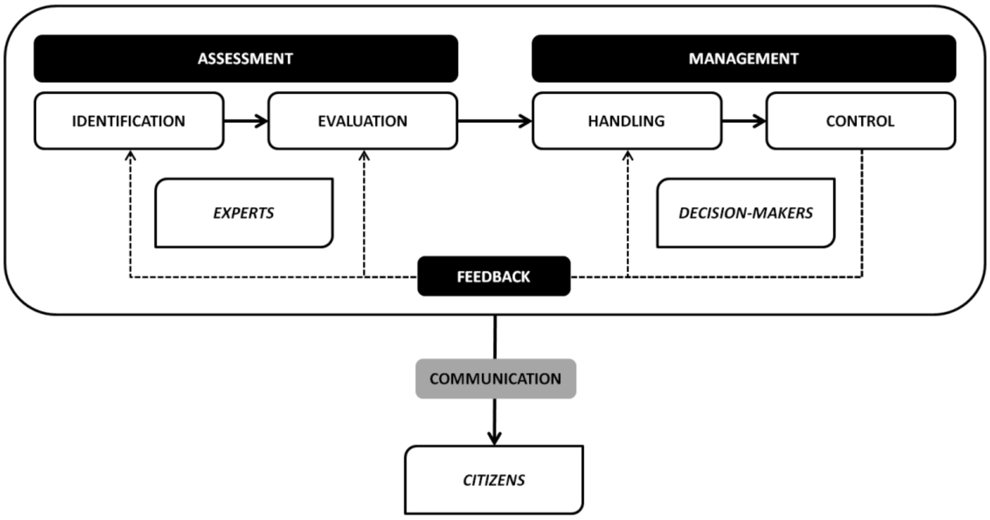


Figure 4. Classical approach of risk analysis

Answering those questions helps identifying, quantifying, scaling and evaluating risks and their associated impacts. Several tools can be used for assessing risks, for instance risk mapping or modelling (Brunet and Schiffino, 2012b). Starting from risk assessment outputs, risk managers have to determinate their priorities according to available risk management options and associated benefits or costs (*handling*). Finally, they have to verify how the responses are matching with initial objectives and what should be the additional measures to take (*control*). Risk management process can be summarized by a second set of triplets, proposed by Haimes (1991):

- What can be done and what options are available?
- What are their associated trade-offs in terms of costs, benefits, and risks?
- What are the impacts of current management decisions on future options?

Several measures can be implemented to handle the risk, depending on the risk acceptance level (see 1.4). Generally, risk management measures are of three types, aiming at avoiding, reducing, or changing the risk, by, for instance:

- Avoiding the risk by not starting or carry on activities that give rise to it;
- Removing its source;
- Changing the likelihood;
- Changing the consequences (mitigation);
- Sharing the risk with another party or parties (i.e. insurances);
- Retaining the risk by informed decision;
- Preparing contingency plans;
- Etc.

However the classical approach, despite its widespread use, presents some limitations regarding the management of more complex risks, especially in the environmental field characterized by an high inherent uncertainty (Bridges, 2003). Another weakness of classical risk analysis is its inability to detect the emergence of systemic risks and/or to analyse them (Renn and Klinke, 2004). Finally, two major criticisms rely to the lack of communication with stakeholders and the ignorance of external concerns.

1.3.2. Risk governance approach

Systemic risks are not amenable to the reductionism of the classical risk analysis approach because they are complex, stochastic and non-linear (Renn, 2016). An holistic and circular framework has been proposed for this purpose: the risk governance framework (IRGC, 2005). According to the International Risk Governance Council, the term governance refers to "*the actions, processes, traditions and institutions by which authority is exercised and collective decisions are taken and implemented*" (IRGC, 2007).

The risk governance – or *post-modern* – model is an integrated approach, because it fosters a more interdisciplinary and qualitative risk assessment, taking in account scientific, economic, social and cultural inputs, and several time and decisional scales in a same process (Shlyakhter et al., 1995). As highlighted on Figure 5, the risk governance approach put the communication at the centre of a circular process, which can be virtually divided between assessment and the management spheres. The role of the communication, which in the cornerstone of the risk governance process, will be discussed in a next section (1.5).

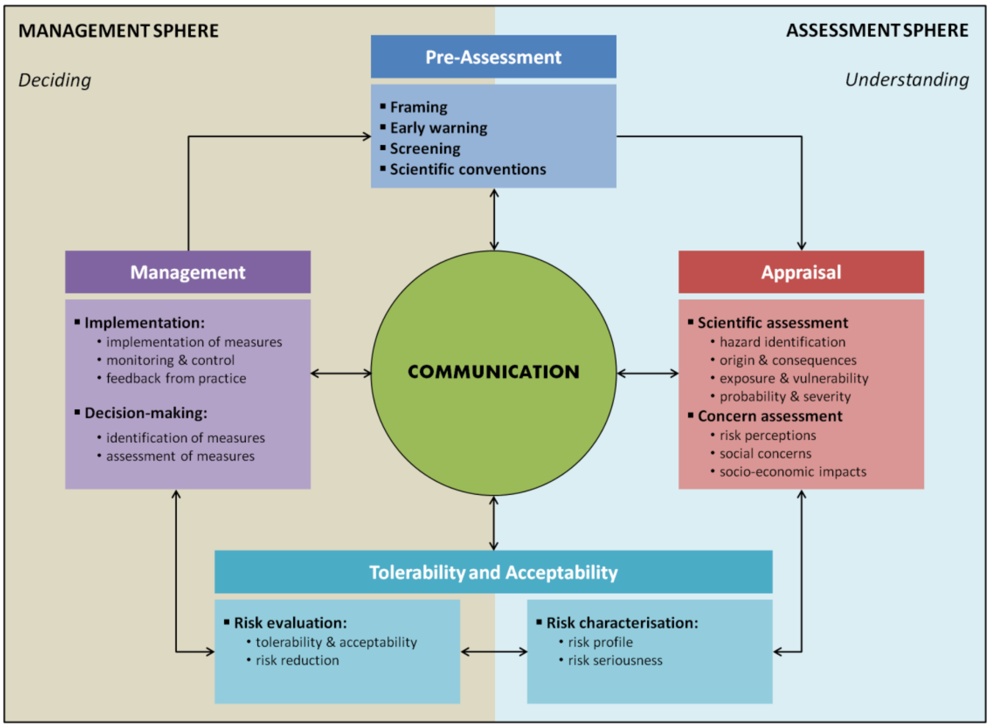


Figure 5. Risk governance framework (adapted from IRGC (2005))

During the pre-assessment phase, a systematic review of what major stakeholders (governments, companies, the scientific community and the citizens) select as risks and what types of problems they label as risky should be done (Aven and Renn, 2010). Framing the risk helps clarifying the various perspectives on it and the issues to cope with (IRGC, 2007). Furthermore, pre-assessment is also fed by early warnings, which result from systematic searches for detecting hazards and threats, in particular emerging risks. The establishment of screening procedures and scientific conventions also concur to the pre-assessment stage.

The main goal of the appraisal step is to provide the necessary knowledge for decision-making. As in the classical approach, a scientifically-based assessment is done, in order to identify and quantify the hazard, exposure, vulnerability and probability of damage. However, in contrast with the classical approach, the risk governance process includes societal and economic concerns, as well as stakeholders' perceptions. The concern assessment is the key element of the risk governance framework, because it ensures that decision-makers account for how the risk is perceived when values, emotions and human behaviours come into play (IRGC, 2007). Once again, the perception and acceptability of risk are strongly influencing the risk management process (see next section).

The next steps are twofold and virtually located at the interface between assessment and management spheres (see Figure 5). According to Aven and Renn (2010), risk characterisation and evaluation processes both serve two main purposes. First, they aim making a value-based judgement about risk tolerability and acceptability or performing a trade-off analysis of a set of strategies. Second, they initiate the management process, if necessary, by making suggestions about the most suitable management measures. In this context, tolerable means that an activity is justified according to expected benefits, however, risk handling measures are mandatory to reduce the risk associated to it under a reasonable threshold. Acceptable means that risk reduction is considered unnecessary. Intolerable means that the risk should be avoid or prohibited. It is useful at this stage to map risks according to their acceptability and tolerability (IRGC, 2005), by drawing for instance a risk diagram with probabilities on the y-axis and extent of consequences on the x-axis (Figure 6). This kind of diagram, also known as "traffic light model" helps to figurate in which situation a decision-maker stands. As an illustration, the yellow part indicates a tolerable risk in need of further management measures for reducing it as low as reasonably possible (ALARP principle). However, drawing the line between 'intolerable' and 'tolerable' parts as well as 'tolerable' and 'acceptable' parts is one of the most difficult and challenging tasks of risk governance (IRGC, 2007). This type of risk mapping as been proposed, for instance, by Gardiner and Quine (2000) in the process of managing risk to reduce wind damage in forests stands (see next chapter).

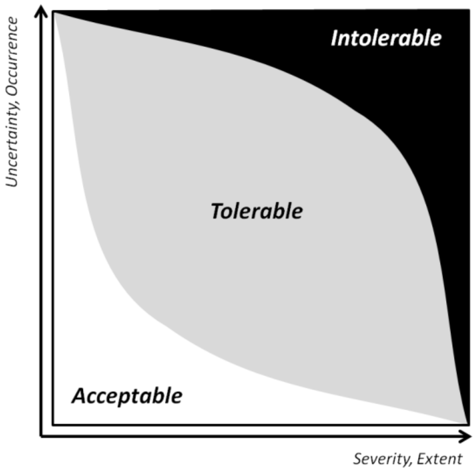


Figure 6. Acceptable, tolerable and intolerable risks (Basic Traffic Light Model)

Finally, risk managers must design and implement measures for avoiding, reducing, transferring or retaining the risks, in regards to the three potential outcomes (acceptable, tolerable and intolerable risk) and in accordance with risk perceptions. In other words, risk management can be viewed as the process that identify, generate, assess, evaluate, select, implement and monitor risk management options. For these purposes, decision-makers can use, among others methods, Cost-Benefit Analysis (CBA) and Decision-Supporting Tools.

1.4. PERCEPTION AND ACCEPTABILITY

The risk perception is the subjective judgment that people make about the characteristics and severity of a risk (Slovic et al., 2004). Several theories tried to explain why different people make different judgments about the same risk, mostly in psychology (heuristics and cognitive), sociology (cultural theory) or interdisciplinary fields (social amplification theory). Studies in psychology about Decision Research first drawn the hypothesis that biases in risk judgment revealed heuristics of thinking under uncertainty (Tversky and Kahneman, 1974). The *Psychometric paradigm* (Slovic, 2000) looked for its part at how people react emotionally to a risky situation that affects their judgment. Research in psychometrics has demonstrated that perceived risk is highly dependent on intuition, experiential thinking, and emotions, more particularly: *i)* the degree to which a risk is understood, *ii)* the degree to which it evokes a feeling of dread, and *iii)* the number of people exposed to the risk (Burns and Slovic, 2012). This theory is particularly suitable for the specific case of extreme events (Slovic and Weber, 2002).

Under the sociological approach of risk, perceptions are supposed socially constructed by institutions, cultural values, and habits. The *Cultural Theory of risk* (Douglas and Wildavsky, 1982) explains risk perception through the way people are bound by both their social role and feelings of belonging or solidarity. Combined researches in psychology, sociology and communications also tried to explain why some relatively minor risks, as assessed by technical experts, could raise strong public concerns and result in substantial impacts upon society and economy. This phenomenon, termed as the *social amplification of risk* by Kasperson et al. (1988), is underpinned by the thesis that hazards interact with psychological, social, institutional, and cultural processes (*filters*) in ways that may amplify or attenuate public responses to the risk, and therefore generate secondary impacts (*ripple effects*). Readers can refer to Kasperson et al. (1988) for a detailed conceptual framework of the social amplification of risk.

Choices and decisions during the risk management phase thus largely rely on decision-makers' perception of the risk in stake, because it influences their willingness to accept risks or not (Kärhä, 1998). The risk aversion, or willingness to avoid risks, can be quantified with several methods (Brunette et al., 2015a). Risk aversion may lead to complete inaction as more risk averse decision-makers will get higher utility from holding on the money than spending it on either risk prevention or control (Finnoff et al., 2007). This is a reason why personal judgements should be integrated and assessed in every risk analysis process. Nevertheless, personal judgment may vary through the time for the same person, depending on how decisions are framed (Sample et al., 2014), in which context they are made (Brunette et al., 2014), what are the characteristics of hazards (McDaniels et al., 1995) and how they are presented by media to people (McFarlane et al., 2015).

1.5. COMMUNICATION

In the classical approach, the communication is considered as a tool for reducing the gap between the reality that is stated by experts and its skewed perception by citizens (Chevassus-au-Louis, 2007). Communicating thus only aims making the average layperson aware of risk management measures. This kind of unidirectional communication should rather be called "information", because the recipients are not involved at all in the risk analysis process (see Figure 4) and are supposed to implement without any criticism decisions that are scientifically-based (Brunet and Schiffino, 2012b).

In contrast, communication is at the cornerstone of the risk governance approach, whatever the step (Figure 5), and every stakeholder is invited to share their opinions and values about the risk at stake, both during assessment and management phases. This 'inclusive governance' is based on the hypothesis that all stakeholders have something useful to bring into the governance process and moreover that this inclusion will improve the quality of and the confidence in decisions. In addition to their Risk Governance Framework, the IRGC (2007) also suggested a framework for involving stakeholders in the decision-making process regarding the dominant characteristic of the risk (Figure 7). Participatory processes are also useful at this step to help reaching common agreements among stakeholders (Ananda and Herath, 2003a).

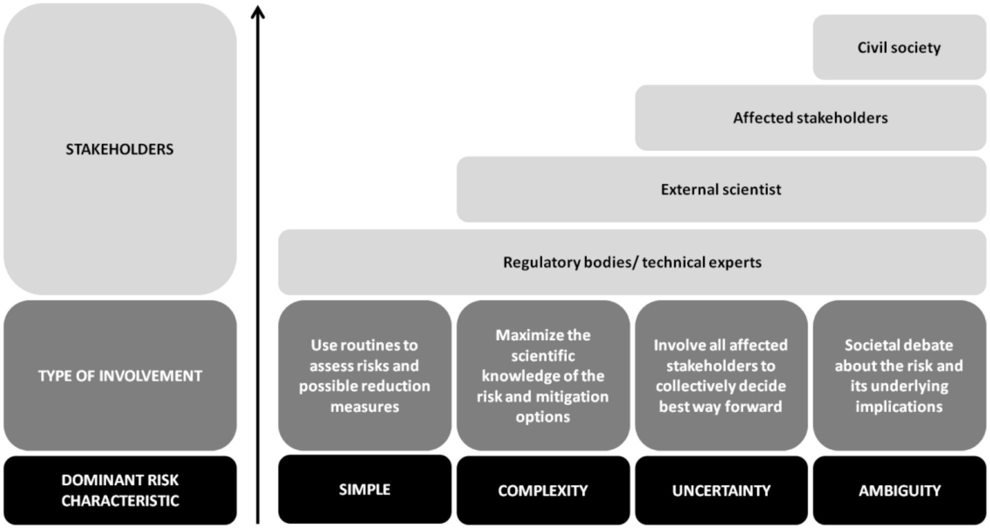


Figure 7. Proposed framework for an inclusive governance (adapted from IRGC (2007))

2

STORM DAMAGE IN FORESTRY

This chapter presents an overview of storm damage assessment and management in the forest sector, based on the concepts presented in the first chapter. It particularly highlights how storm impacts can be classified and assessed. It also presents briefly the storm damage management process and the way to manage forest risks under climatic uncertainty.

2.1. DEFINITION

The risk of storm damage is the interaction between the occurrence of the wind hazard (likelihood), the predisposition to damage (vulnerability) and the value exposed to the damage (exposure). It is customary in the windthrow literature to limit the concept of "wind damage risk" to the mechanical effects of wind on trees (Gardiner et al., 2008). However after-effects of huge storms must also be considered as risks, as consequences of windthrow are spreading through the forest-wood chains and are impacting all forest-related activities.

2.2. IMPACTS ON THE FOREST RESOURCE

2.2.1. Damage classification

Damage resulting from windstorms can be classified in three categories:

- **Primary damage** are the mechanical damage caused by the storm to the forest resource, expressed in terms of volume (m^3), area (ha), or growing stock affected (% GS);
- **Secondary damage** encompass subsequent damage to the forest resource, directly linked to the initial event, such as bark beetles outbreaks or fires;
- **Tertiary damage** are the long-term consequences of the storm on forest growth and management.

2.2.2. Wind effects on trees

From a meteorological perspective, winter storms originating from extra-tropical cyclonal processes and generating gust wind speed up to 30 ms^{-1} are prone to cause extensive damage in Europe (Nilsson et al., 2007, Gardiner et al., 2010, Usbeck et al., 2010). However, the relationship between the wind speed and the level of damage is not as straightforward (Bock et al., 2004), because the stand and site characteristics also modulate the severity of damage (Waldron et al., 2013). In addition, local wind climate has also an influence on trees' resistance to windblow. In fact, trees that grew under windy conditions acclimate to local wind climate by strengthening their anchorage (Nicoll et al., 2006) or their strain (Bonnesoeur et al., 2016). Other meteorological factors also influence the level of damage, for instance the precipitation regime before the storm that could cause soil waterlogging and reduce trees' anchorage (Peltola et al., 1999). Interested readers may consult several papers that deal with wind effect on trees for further information (i.e. Schindler et al., 2012, Dupont et al., 2015, Virot et al., 2016).

2.2.3. Vulnerability and exposure

In addition to storm characteristics, the level of damage will also be modulated by exposure and vulnerability factors. In this context, changes in forest composition, structure, and extent are more likely to explain the level damage (Nilsson et al., 2004, Seidl et al., 2011, Thom et al., 2013) than wind features. As an illustration, it was inferred from a selection of 11 destructive storms in Europe that the primary factor controlling the storm damage severity was the standing volume (Gardiner et al., 2010). Since the growing stock in European forests is increasing since 1950 and is still expected to rise in the next century under various management trends (Nabuurs et al., 2007), the exposure to storm damage will remain high. Forest vulnerability must also be taken in account, from tree to stand level. Factors as trees' anchorage (Nicoll et al., 2006, Kalberer et al., 2007) or soil nature (Mayer et al., 2005) can influence vulnerability to wind damage. However, the overall risk can be found lower in places where most severe wind climate prevails, because of the selection of risk-minimising strategies (Moore and Quine, 2000).

2.2.4. Risk assessment

Numerous publications dealt with risk assessment in forestry in the last fifteen years (Hanewinkel et al., 2011) and among this collection almost 14 % of papers addressed wind damage (Yousefpour et al., 2012). The main goal of storm damage risk assessment is to inform forest managers about the silvicultural practices that are influencing the risk of damage (Jactel et al., 2009, Albrecht et al., 2012) and how they can cope with it in daily forest management and planning (Heinonen et al., 2009). Existing literature covers a broad range of topics: wind-susceptibility of trees species (Schütz et al., 2006, Yoshida and Noguchi, 2009, Albrecht et al., 2013), impact of silvicultural treatments (Mason, 2002, Schelhaas, 2008, Mason and Valinger, 2013, Agbesi Anyomi and Ruel, 2015) or consequences of harvesting or thinning operations (Lanquaye-Opoku and Mitchell, 2005, Byrne and Mitchell, 2013). In order to assess the probability of wind damage, quantitative modelling approaches are mainly used, either at tree, stand or landscape level (Kamimura et al., 2015). Most of time, models are based either on empirical or mechanistic approaches.

Empirical methods are based on field observation, historical records and extensive literature reviews (Hanewinkel et al., 2011). Usually the risk of damage is assessed at tree, stand, or landscape level, although some recent papers were using large-scale database originating from national forest inventories to the enlarge assessment scale (Schmidt et al., 2010, Usbeck et al., 2010, Moore et al., 2013). Empirical methods are frequently used in the literature (Dobbertin, 2002, Lanquaye-Opoku and Mitchell, 2005, Hanewinkel et al., 2008, Schindler et al., 2009, Schmidt et al., 2010, Klaus et al., 2011, Valinger and Fridman, 2011, Albrecht et al., 2012, Albrecht et al., 2013), also for simulating bark beetles outbreaks following windstorm (Jönsson et al., 2012, Stadelmann et al., 2013, Wermelinger et al., 2013). This approach also allows investigating the influence of site factors as well as trees and forest stands parameters on damage severity and provides indications on the impacts of forest management scenarios (Jactel et al., 2009). A main drawback is that probabilities may not be valid as there have been changes in the population being studied (Quine, 2005), since trees and stands characteristics change dynamically along with forest growth (Peltola et al., 1999). Nevertheless it is possible to take in account microclimatic changes due to windthrow within forest stands by 'removing' the damaged trees from the modelling process (Panferov et al., 2009). Climate-sensitive forest growth models are used too to cope with changes in forest composition or productivity over time (Blennow et al., 2010) and to predict wind damage at regional scale (Lagergren et al., 2012).

Nonetheless, statistical approaches are not explaining relationships between tree parameters and vulnerability to wind (Gardiner et al., 2000) and provide only general insights into the mechanisms of windthrow (Gardiner et al., 2008). That is why mechanistic models have been developed to calculate wind damage probability on the basis of trees' resistance to wind. The initial step is to calculate the above-canopy 'critical wind speed' (CWS) required to break or overturn trees within a forest, on the basis of experiments investigating physics of tree failure, like anchorage or stem breakage, with tree pulling experiments (Nicoll et al., 2006) or wind tunnel investigations (Gardiner et al., 2005). The second step is to use assessments of the local wind climatology to calculate the probability of such a wind speed occurring at the geographic location of the trees (Gardiner et al., 2008). The coupling of CWS and wind climate models into wind risk management (WRM) tools allows inferring the resulting probability of damage.

This kind of approach has been implemented in several locations worldwide (Ancelin et al., 2004, Cucchi et al., 2005, Schelhaas et al., 2007, Kamimura et al., 2008), some of these studies taking in account the changing wind climate in the process (Blennow and Olofsson, 2008) or simulating the propagation of windthrow during wind events (Byrne and Mitchell, 2013). However, regarding decision-making, the main disadvantage of mechanistic models pointed out by Gardiner et al. (2008) is its inherent complexity that can lead to repulse end-users of using it. If the models are too complex, then only specialized and expert users may be able to operate them. Ideally, assessments should be coupled with decision-support methods, for instance decision tree (Kamimura et al., 2008), to make them understandable by decision-makers. The calculated risk can also be reported on susceptibility maps (Ruel et al., 2002, Blennow and Sallnäs, 2004, Ionut and Bogdan, 2012). For example, Zeng et al. (2007) built a GIS-based decision-support system that allows evaluating and visualizing in charts and graphs the risk of damage associated to various management practices over time in Scandinavia. Schindler et al. (2009) and Jung et al. (2016) also quantified the probability of damage for a regional case study in Germany using GIS tools.

Mechanistic models are usually more appropriated for large-scale assessments (Gardiner et al., 2008), only in locations presenting soil conditions similar to where the model parameters were obtained from previous field experiments (Kamimura et al., 2015). On the other hand, empirical modelling cannot be generalized to regions from which data has not been obtained (Moore and Somerville, 1998) without a complete and time-consuming re-parameterization. As a consequence, trade-offs between the level of assessment and the expected output are necessary. For example, Dhubhain et al. (2001) have developed a risk management tool that assesses the probability of windthrow for the whole Irish territory, but with limited inputs (stand height, type of soil and thinning operations) and a very large degree of uncertainty for predictions. Another way to aggregate results from local to global level is to use expert knowledge or decision support systems (DSSs) in combination with the results of models (Mitchell, 1998, Mickovski et al., 2005, Olofsson and Blennow, 2005, Kamimura et al., 2008).

2.3. IMPACTS ON THE FOREST SECTOR

2.3.1. Multidimensionality

The multidimensionality of windthrow crises is often reduced to one specific impact, either for operational or sectoral purposes. However, the previous classification of damage is only suitable for assessing and managing the risk of wind damage in regards to the productive role of forests. Indeed, it does not integrate direct and indirect consequences on other activities based on and services provided by forests. A wider risk assessment must be done, in order to evaluate the after-effects of storm damage on these activities and functions. If the multifunctionality of forest is used as an analytic framework, it means that productive, protective, societal, recreational and environmental aspects should be screened. Another criterion could be the sustainability of the forest sector, which can be addressed through economic, environmental and social perspectives. This assessment should be done at local, regional, and supra-regional scale. In other words, a multidimensional risk analysis is necessary to catch the whole picture.

2.3.2. Environmental impacts

Wind hazards are natural drivers of forest ecosystems (Ulanova, 2000, Mitchell, 2013), and thus storms can have a positive impact on local biodiversity (Lang et al., 2009), provided the damaged areas are managed in accordance with this purpose. However, huge storms could also have harmful consequences for managed forest (Payn et al., 2015), by altering both timber production and the delivery of goods and services. For instance, soil fertility could be reduced due to uncontrolled salvage operations (Spinelli et al., 2013), while protective role of forest against erosion, rockfalls, landslides or snow avalanches could be weaken (Schönenberger, 2002b, Teich and Bebi, 2009). Destructive storms also threaten carbon mitigation strategies (Canadell and Raupach, 2008). In Europe, effects of afforestation and changes in mean growing stock volume have increased positively carbon sinks (Vilén et al., 2016), but the carbon balance may be overestimated when wind disturbances are not taken in account (Fortin et al., 2014). Strategies settled by national governments for reducing CO_2 emissions, especially in the post-COP21 context, could failed if natural disturbances are not taken in account in the process (Kurz et al., 2008, Lindroth et al., 2009, Thürig et al., 2013). Finally, detrimental impacts on forest health are probably the more tangible threat in the aftermath of huge storms. Among phytosanitary risks, bark beetles (*Ips typographus*) outbreaks are frequently causing secondary damage, ranging from 10 to 20% of initial amount (Stadelmann et al., 2013). Furthermore, phytosanitary risks are also threatening standing healthy stands surrounding damage areas. Consequently, a growing attention has been paid to the dynamics of population since 1999's storms (Wermelinger et al., 2002, Bouget and Duelli, 2004, Jönsson et al., 2012, Wermelinger et al., 2013, Mezei et al., 2014) in order to mitigate secondary damage by pests.

2.3.3. Economic impacts

Economic impacts of storms are manifold. The forest-based sector is affected by windstorms in its different components, throughout the forest-wood chains, from the forest owners to the forest-based industry. Primary damage cause financial losses, proportional to the type of mechanical damage (broken or uprooted trees). Forest owners are concerned with those direct financial consequences on stumpage prices (Nieuwenhuis and O'connor, 2001a) and also by future revenue losses due to earlier harvesting (Nieuwenhuis and O'Connor, 2001b). This loss of income is coupled with the increased costs of salvaging these stands (Magagnotti et al., 2013). In France, the pecuniary losses for forest owners were estimated around 6 billion euro for the Lothar and Martin storms (Peyron, 2002), and between 1.34 and 1.77 billion euro for the Klaus storm (Costa et al., 2009). Secondary damage (pests, fires) can also cause supplementary losses. For industries, storms affect roundwood prices and procurement over mid and long-term. Whereas lower prices mean cheaper raw material for forest-based industries, the benefit does not always go to local enterprises in a globalized timber market. In addition, the short term surplus of wood supply after the storm is likely to be followed by a local supply shortage in the medium terms without any mitigation measure (Schwarzbauer and Rauch, 2013). Competition between industries for cheaper raw material can also lead to bankruptcies and overinvestment.

2.3.4. Societal impacts

Severe storms have also consequences for the population as they may disrupt communication networks and power supply for days. Windstorms also cause accidents and casualties resulting both directly and indirectly from fallen trees or timber salvage in dangerous conditions (Blennow and Persson, 2013). More generally, storms can affect forest owners and population’s wellbeing in the long-run.

2.3.5. Risk assessment

There are few papers in the literature which are linking the initial amount of wind damage with the potential impacts on the forest sector. Impacts on stumpage prices and profitability can be broadly foreseen (Nieuwenhuis and O'connor, 2001a) as well as extra-damage due to bark beetles outbreaks in the follow-up of larges disturbances (Jönsson et al., 2012). The difficulty comes from the implementation of existing risk management measures when assessing these impacts.

2.4. RISK AND CRISIS MANAGEMENT AT A GLANCE

Risk management strategies concerning storm damage are to three kinds (Figure 8). First, the risk of storm damage can be mitigated through silviculture and forest management, in order to reduce vulnerability and exposure. A portfolio of measures can be implemented, regarding trees (Schmidt et al., 2010, Albrecht et al., 2013) or stands characteristics (Valinger et al., 1993, Schelhaas et al., 2007, Virot et al., 2016). However, the complex interactions between site and stand conditions, as well as with local climate conditions make those considerations uncertain (Quine, 2005). For example, the benefit of creating mixed stands to enhance their stability, as suggested by some authors (Schütz et al., 2006, O'Hara and Ramage, 2013) is not as evident since no clear stability effect has been proven yet (Schelhaas, 2008). Another mitigation option is to share the risk, through insurances or rescue funds for instance, in order to transfer the financial consequences of storm damage from one party to another, or from the public to the private sector (Birot and Gollier, 2001). Finally, the last option is to accept the risk and develop a strategy for coping with its outcomes. This may be the case when the cost of preventive measures is too high regarding the level of risk, or when the residual risk remains too high even after preventive measures.

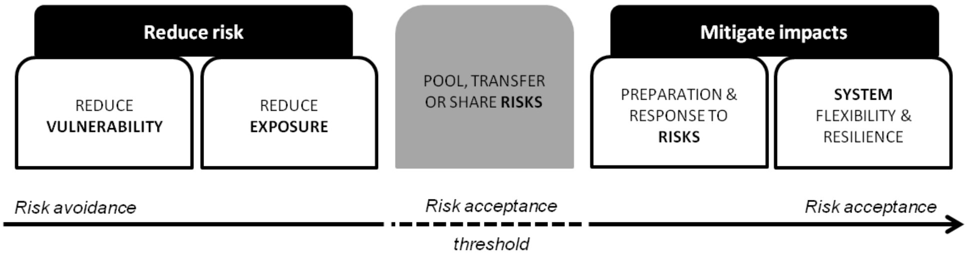


Figure 8. Risk management options

Increasing the systemic resilience means in this context to strengthen the stability of a system. The goal is that the system at stake (for instance the forest ecosystem or forest-based sector) could be able to return as soon as possible to the reference state (or dynamic) after a temporary disturbance (Grimm and Wissel, 1997). This new state could be different from the initial that was prevailing before the storm as such disturbances also give the opportunity to redefine the strategy.

Preparation and response to storm impacts also follow a circular and iterative framework (Figure 9). During the preparation step, the strategic and operational aspects should be defined and implemented. It implies developing or reviewing the contingency plan, training stakeholders, developing early warning systems, etc. After the storm, the response phase aims first at supporting emergency operations. Regardless to the storm severity, population health and safety will always be a primary consideration in the first days following the calamity. Public forest services, forest-based actors and industry play indeed an active role in this initial response, together with the civil services. In as second time, the goal is to assess storm impacts and define a regional strategy to mitigate them. Finally, the recovery phase aims at implementing mid and long term measures for supporting the forest sector.

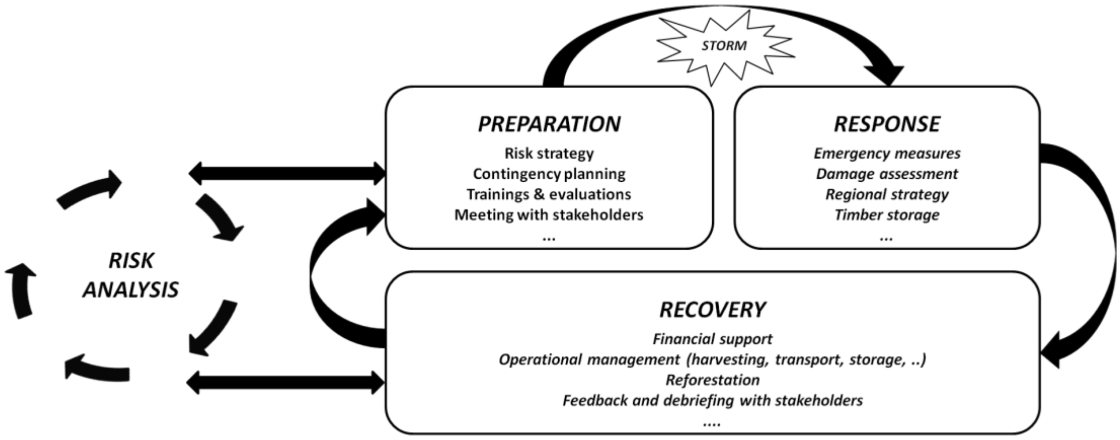


Figure 9. Preparation, response and recovery phases

These successive phases take place in various time-horizons and imply several decision-makers, stakeholders and users. As an illustration, the preparation phase may last for decades before a cataclysmic event happens (this is the case of Belgium), but sometimes the forest-based sector hasn't yet totally recovered from previous event when the next storm strikes, for instance in Aquitaine region (France) with the successive gales Martin, in 1999, and Klaus, in 2009. Thus, the recovery period often merge with the preparation to the following event, and further risk analysis process should be initiated as quickly as possible during the recovery stage.

2.5. MANAGING FOREST RISKS UNDER CLIMATIC UNCERTAINTY

Climate change in the 21st century will likely have several major impacts for forest management and related activities. In Europe, climate change is expected to influence species distribution, and those biome shifts will globally lower the economic value of forests (Hanewinkel et al., 2013). It will also impact the competition between species (Kunstler et al., 2016) and the trees' survival within forest stands (Neuner et al., 2015). The increase of atmospheric CO_2 content could also have positive impacts on forest growth and wood production (Campioli et al., 2012). Climate change is also expected to affect forest processes and structure by altering the frequency, intensity, duration, and timing of key hazards like fire, insects, and windstorms (Dale et al., 2001).

Whereas the effect of climate change on storminess remains uncertain (Albrecht et al., 2009), it will likely affect the risk of storm damage in forests. Indeed, the frequency as well as the intensity of storms will likely change in mid-latitudes in continental regions (Leckebusch et al., 2006, Blennow and Olofsson, 2008). In Central and Western Europe, higher surface wind speed (Fink et al., 2009, Schwierz et al., 2010, Gregow et al., 2012) and shorter return-periods (Karremann et al., 2014) could be expected. This intensified wind disturbance regime is expected to be among the most detrimental impacts of climate change on forest ecosystems (Dale et al., 2001, Lindner et al., 2010). As a result, the higher productivity will probably be outweighed by the higher exposure to storms (Lindner et al., 2010) and the carbon mitigation potential of forests could be affected (Lobianco et al., 2015). Adapting forestry and forests to climate change thus request a change of paradigm compared to traditional forest management practices (Schoene and Bernier, 2012). Furthermore, uncertainties linked to climate change must also be considered in the adaptative management process (Yousefpour et al., 2012). Regarding climate change impacts, several adaptation options are offered to decision-makers (Bolte et al., 2009):

- Carry on with business-as-usual strategies ("do nothing")
- Reactive adaptation to new conditions ("wait and see")
- Active adaptation of forest management practices
- Conservative approach ("robust")

The choice between those strategies is driven by several factors: the severity of impacts, the value at risk and the decision-makers' risk aversion (confer 1.4). As mentioned by Subramanian et al. (2015), deeper analyses assessing the effects of anticipated climatic changes on damage levels, and the potentially relieving effects of adaptations measures are highly needed before implementing those changes. Furthermore, it requires sound understanding of the effects of climate on forests, industries and communities in order to include this knowledge into management decisions (Keenan, 2015).

3

INTEGRATED APPROACH OF STORM DAMAGE RISK

This chapter presents an original approach for handling storm damage management issues. In a first step, Strengths, Weaknesses, Opportunities and Threats in the current approaches are analysed from both forest-based sector and public authorities' angles. In a second step, integrated and systemic approaches are suggested to improve the storm damage management process. Finally, recommendations are given to public authorities in order to improve their involvement in this process.

This chapter is a transcription of the following paper:

> RIGUELLE, S., HÉBERT, J. & JOUREZ, B. (2016). Integrated and systemic management of storm damage by the forest-based sector and the public authorities. *Annals of Forest Science*, 73, 585-600.

3.1. INTRODUCTION

Worldwide, windstorms are among the major abiotic threats for planted forests (Payn et al., 2015), and in Europe they have contributed to more than the half of the total damage to forest resources since 1950 (Schelhaas et al., 2003). Even though wind hazards are natural drivers of forest ecosystems (Mitchell, 2013), destructive storms that occur over large areas in managed forests lead to severe economic losses for the forest-based sector (Björheden, 2007) and offset benefits resulting from higher forest productivity (Fares et al., 2015). For example, the total insured losses, including forestry, due to the storm series of 1999 exceeded €10 billion (Munich Re, 2002). The total economic losses resulting from those events were estimated at around twice as much (Pinto et al., 2007). From an industrial angle, destructive storms are usually defined as hazards that blow down 100% or more of the average annual harvest at the scale of industrial supply (Forestry Commission Scotland, 2014). This sudden amount of timber to cope with threatens the normal functioning of forest-based activities (Valinger et al., 2014), disrupts the classical management and decision-making processes (Angst and Volz, 2002, Broman et al., 2009), and consequently causes critical situations within public and private organizations (Drouineau et al., 2000, Birot et al., 2009). Regarding timber market, prices and supply may be heavily impacted over the long run when several supply areas are experiencing severe damage at the same time (Costa and Ibanez, 2005). From an environmental perspective, wind disturbances may cause a huge reduction of forest carbon sinks (Lindroth et al., 2009), lead to pest outbreaks (Wermelinger et al., 2013), or weaken the production of goods and services of forests in damaged areas (Lindner et al., 2010). In addition, society is also affected by the consequences of storms, i.e. occurrence of civil casualties, alteration of landscapes, and of living conditions (Blennow and Persson, 2013).

In light of those potential impacts, active management of storm damage risk should appear logical. Paradoxically, even though destructive storms have been part of the history of European forests for a long time (Corvol, 2005), this only became obvious in the 1990s, after a succession of shock events that led to questions regarding major changes in forest management (Birot, 2002, Veenman et al., 2009). As a result, literature on risk management in forestry exponentially increased in the 2000s (Yousefpour et al., 2012), and a large body of knowledge in now available. This new paradigm within the forest community is also driven by several external factors. One of them is the macro-economic context, particularly the need to stay competitive in a globalized timber market and thus to limit the costs related to natural hazards (Meyer et al., 2013). Other impulses ensued from uncertainties linked to expected impacts of climate change on forest storm damage (Spathelf et al., 2014, Keenan, 2015, Schou et al., 2015). Among others, the potential shift in winter storm frequency and severity (Fink et al., 2009, Schwierz et al., 2010), the continuous increase of the economic value at risk owing to the capitalization of growing stock (Nabuurs et al., 2007), and the higher vulnerability of forest stands (Campioli et al., 2012) are expected to increase the risk of damage. Societal changes also generate increasing economic losses from natural disasters (Barredo, 2010). Therefore, in accordance with the "*Risk Society*" concept (Beck, 1992), the management of hazards and insecurities in our modern societies tends to be one of the main preoccupations of public decision-makers (Brunet, 2007). Nowadays, in this new perspective of modernity, politics are more prone to deal with the after-effects of huge storms and actively take part in the process (Barthod and Barrillon, 2002). Whatever the initial motivation, it is now clear that both the forest-based sector and the public authorities cannot avoid addressing storm damage risk. The question is how to do this soundly and effectively?

Through the years, a methodological framework to address storm damage risk in forestry was gradually formalized on the basis of the classical theory of risk management (Haimes, 2004) and international standards (ISO 31000), and was used in several papers (Gardiner and Quine, 2000, Kamimura and Shiraishi, 2007, Schelhaas et al., 2010, Hanewinkel et al., 2011). This framework consists of an iterative assessment process that allow decision-makers to quantify risk —where the term *risk* encompasses the large variety of risks resulting from destructive storms—and implement mitigation strategies in order to reach the desired level of residual risk. For this latter purpose, decision-makers have to know what the options are, what the costs and benefits are, and know the residual risk associated with policy options (Kaplan and Garrick, 1981). In a second step, if the residual risk remains too high to be acceptable, tools and procedures to support crisis management may be developed, such as decision-support systems, contingency plans, trainings, and exercises. Finally, if the destructive storm occurs, the response phase will be activated. It first consists of an immediate crisis response period with a special focus on emergency and rescue operations, timber damage assessment, and safeguarding measures. After the emergency phase, a public strategy should be implemented to support the forest-based sector. Again, public decision-makers will have to choose between a set of strategies encompassing the particular interests of stakeholders, and public constraints. The more efficient the strategy is, the quicker the forest-based sector will recover from the shock and stabilize to a new equilibrium.

Despite the methodological improvements and the large body of literature addressing specific storm-related issues in forestry over the last fifteen years, several papers recently reported the need to improve decision-making and management of storm damage at the strategic level (Gardiner et al., 2010, Gardiner et al., 2013, Landmann et al., 2015). However, as indicated previously, storm damage management is a highly complex, uncertain and ambiguous process, because of the multiplicity of risks, stakeholders, goals, and beliefs. As it is impossible to eliminate those elements from the risk management process, new approaches to address them effectively must be provided to the forest-based sector and the public authorities. Furthermore, the role of public authorities has to be clarified in regards to the forest community's expectations. Indeed, in the past, initiatives from the forest community did not always receive the expected responses from public authorities (Birot et al., 2009). In this context, it seemed relevant to re-open the debate on how windthrow crisis management may be improved at the strategic level and what the role and interactions of the forest community and public authorities should be in this effort. The target of this paper is thus to provide a blueprint for how to progress in the future, identify where the priorities are, and suggest how some of them should be addressed. The first step is to identify issues and opportunities for stakeholders, using SWOT analyses based on recent storm experiences and the relevant literature. The second is to present a holistic approach for addressing storm damage risk at the regional (or national) level, and describe the way to mitigate risk and support decision-making according to this framework. A focus on the specific role of public authorities is presented in a third step.

3.2. STRATEGIC ISSUES AND OPPORTUNITIES

3.2.1. Methodology

SWOT methodology was chosen to identify current strengths, weaknesses, opportunities, and threats in the storm damage management process from both the forest-based sector and public authorities' perspectives. This allows the internal factors that can be handled directly by decision-makers from both groups to be distinguished, and identifies the external elements they need to address to build their risk management strategy. It also contributes to highlighting common features and reveals the inherent relationships between these two types of stakeholders. A broad literature search focusing on "risk and crisis management in forestry" was done using different search engines. This resulted in a list of approximately 250 relevant papers. However, few of them provided a global analysis of storm damage crisis approaches. Therefore, several ex-post crisis evaluations—either governmental reports or publications by public bodies and private institutions (see Table 1)—were also reviewed. Analyses of recent storm crises in European countries are indeed good entryways to identifying limits and failures in classical approaches (Trauman, 2002).

Table 1. Selection of ex-post evaluations of storm crisis management strategies in Europe

Scope	Storm (Year)	References
Europe	Selection of storms	Gardiner et al. (2010, 2013)
France	Lothar - Martin (1999)	Drouineau et al. (2000); Barthod and Barrillon (2002)
		Lesbats (2002); Birot et al. (2009), FIBOIS (2010b)
	Klaus (2009)	Nicolas (2009); Laffite and Lerat (2009)
		GIP ECOFOR (2010); Bavard et al. (2013)
Germany	Lothar (1999)	Hänsli et al. (2003)
Sweden	Gudrun (2005)	Swedish Forest Agency (2006)
Switzerland	Lothar (1999)	Bründl and Rickli (2002); Hammer et al. (2003)
		Hänsli et al. (2003) ; Raetz (2004).
UK	The Great Storm (1987)	MAFF (1988); Grayson (1989); Harmer (2012)

3.2.2. SWOT analyses

Table 2 presents the outputs of the two SWOT analyses. Only the most significant topics regarding strategic decision-making and crisis management were retained after the review process. Tactical and operational issues are not considered, except as they arose because of strategic concerns. The results are briefly discussed below.

Forest managers usually have a good perception of the exceptional nature of destructive storm events, and thus are prone to react quickly after calamities (Direction des Forêts, 1987, Swedish Forest Agency, 2006). The downside to this strong empirical knowledge may be a reluctance to manage actively the risk of storm damage, as stakeholders generally consider windstorms from a fatalistic perspective (Peyron et al., 1999). At the same time, knowledge about the operational management of windthrows has strongly increased in the last decades because of former crisis experiences and an increasing scientific focus on this topic. Numerous technical handbooks, sometimes released in emergency just after a storm, already support decision-makers and managers (Forest Windblow Action Committee, 1988, FAO/ECE/ILO, 1996, Pischedda, 2004, Odenthal-Kahabka, 2005, OFEV, 2008, Oosterbaan et al., 2009). However, the share of knowledge among scientists and practitioners may remain problematic. The *Storm Handbook* (Odenthal-Kahabka, 2005, Chtioui et al., 2015), which evolved progressively from a print to an on-line version, is a good illustration of how information policy about windstorms has changed over the years to address the lack of accessibility and applicability of information (Hartebrodt, 2014).

Table 2. Overview of most frequent strengths, weaknesses, opportunities and threats regarding strategic decision-making and management of storm damage by the forest-based sector (FBS) and public authorities (PA)

	Forest-based sector (FBS)	Public authorities (PA)
STRENGTHS	- Strong operational know-how - Strong empirical knowledge - Large body of scientific knowledge	- Financial capacity - Legislative power - Regulatory levers
WEAKNESSESS	- Reluctance to manage risks - Limited common strategy - Short versus long-term goals - Private versus public behaviours - Lack of financial liquidity - Few long-term impact assessments - Share of knowledge (all levels)	- Lack of public risk governance - No integrated policy for forest risks - Unclear storm management strategy - Fragmented and unbalanced approach - Complexity of cost-efficiency analyses - Poor cooperation with other regions/states - Staff, structures and facilities
OPPORTUNITIES	- Advanced decision support systems - Innovation capacity - Development of ICT solutions - Higher expectations towards forest - Coordination initiatives - Increasing scientific knowledge - Emergence of new markets	- Advanced decision support systems - Innovation capacity in the FBS - Development of ICT solutions - Societal expectations towards forests - Increase of societal risk-awareness - Advanced economic impact assessments - Role of forests in climate mitigation
THREATS	- Macro-economic context - Climatic and market uncertainties - Change resistance - Timber market disruption - Reduction of financial support - Inappropriate legislation - Rigid decisional framework - Loss of experienced people - Lack of solidarity	- Macro-economic context - Public expectations - Change resistance - Shrinkage of financial resources - Globalization of timber market - EU competition rules - Uncontrolled ideological issues - Emotional management - Uncertain impacts of climate change

As for disaster risk management in general (Gopalakrishnan and Okada, 2007), the main flaw results from the diversity of stakeholders' beliefs, interests, and goals which complicate the post-storm crisis response. The high fragmentation of forest estates and the multitude of owners, in both private and public forests, also makes difficult to settle a common strategy. As an illustration, the fragmentation of forest estates and the rights of ownership were considered major hindrances to timber salvage during previous crises (Lesbats, 2002). The recurring lack of liquidity also exacerbates the stakeholders' dependence on public compensation. Therefore, the competition for public subsidies in the aftermath of windstorms may enhance individualistic behaviour (Brunette and Couture, 2008). As a result, the forest-based sector often implements uncoordinated and fragmented strategies, which is a major source of inefficiency. Insurance issues also lead to ambiguous behaviours. For instance, too high premiums compared to forest investments often deter owners from subscribing to insurance (Brunette et al., 2015b) and make them dependent of state aid in case of storm damage. Furthermore, when insurance does exist, it compensates primary damage on the forest resource, but rarely subsequent damage resulting from complications (Holecy and Hanewinkel, 2006).

In the past, diverging interests between stakeholders have also weakened the sector's credibility vis-à-vis the public authorities, and complicated negotiations with them (Lesbats, 2002). Individual and sometimes antagonistic strategies contributed to slowing down recovery from storm crises (GIP ECOFOR, 2010), while fragmented approaches have led to a dispersion of financial resources without knowing whether individual measures are cost-effective (Caurla et al., 2015). Consequently, public mitigation measures may cause competitive distortion between stakeholders if the global economic welfare of the forest-based sector is ignored during the decision-making process (Ananda and Herath, 2009). Former experiences revealed that even if public authorities hold the strategic levers, they lack supporting tools and information to build integrated strategies (Gardiner et al., 2010). Usually, forest policymaking follows its own logic, based on diverging interests and values (Winkel and Sotirov, 2015). Even though risk awareness is increasing, significant gaps remain in public risk governance, and public policies do not often encompass risk as the driver of decision-making processes (Blennow, 2008). In a storm crisis context, it results in unpreparedness, overhasty strategies, and the spread of all possible grants (i.e. harvesting, storage, replanting, and marketing subsidies) without cost-efficiency assessments. Owing to the emergency context, crisis management measures are often disconnected from the prevailing macro-economic context (Bavard et al., 2013) although they are determinants of the forest sector's resistance and resilience. In fact, without appropriate economic analyses, the pros and cons of mitigation strategies are not easy to predict. The restricted availability of country-level information on disturbances could make implementing multi-risk strategies even more difficult (van Lierop et al., 2015).

Fortunately, new conditions for storm damage management are emerging. The accessibility to advanced decision support systems (Diaz-Balteiro and Romero, 2008, Reynolds et al., 2008, Marques et al., 2013b, Segura et al., 2014), and the development of powerful ICT solutions (Reynolds et al., 2005) should ease the strategic management of storm damage by both the forest-based sector and public authorities. Innovation capacity in the timber industry will open new market opportunities for windblown timber, and provide favourable market and policy conditions (Buttoud et al., 2011). However, as stated by Nilsson (2015), forest policy-making is not yet an affair between the sector and the public authorities, as manifold stakeholders claim interests and rights to do with the forest. Societal requirements are double-edged elements because even if they increase the role of forest ecosystems, they also force the public authorities and the forest sector to cope with ideological expectations (Ananda and Herath, 2009). Therefore, storm calamities and associated casualties are likely to cause overreactions and political claims (Raetz, 2004).

From an economic angle, a slump in market conditions associated with lower financial public support may threaten the effectiveness of risk management approaches when windstorms occur. Uncertainties relative to market behaviour and long-term wood procurement (Schwarzbauer and Rauch, 2013) are among those economic issues. From the perspective of decision-making, rigid administrative and decisional frameworks, as well as uncontrolled ideological issues (Raetz, 2004) may jeopardize the rapid support to the forest sector. Finally, the loss of experienced people (Hartebrodt, 2014) and fading memories (Harmer, 2012) could make the risk management process less obvious and urgent for forest-based sector stakeholders. Indeed, although damaging windstorms occurred on average twice a year at the European scale during the last 60 years (Gardiner et al., 2010), their frequency is not equally shared at the regional scale. For countries that did not experience destructive storms for decades, such as Belgium, it could be a major hindrance to actively manage the risk (Riguelle et al., 2011). Uncertainties linked to climate change will require flexible and priority-setting approaches on the one hand (Millar et al., 2007), and on the other hand will require a mixed strategy, including adaptation and mitigation measures (Seidl and Lexer, 2013). Even though uncertainties linked to future climate tend to push risk management issues to the top of the forestry agenda, they remain potentially a major source of inertia (Petr et al., 2014).

3.3. INTEGRATED AND SYSTEMIC STORM DAMAGE MANAGEMENT

3.3.1. Advocacy for integrated storm damage management

Integrated management of risks in forestry is an emerging trend that aims to consider simultaneously, at each level of decision, every component of the risk management processes together with external constraints, and the expectations and beliefs of various stakeholders (Orazio et al., 2014). This definition implies that decision-makers must ideally handle together the large variety of risks that face forests in order to reduce the global threat for the forest sector (Drouineau et al., 2000). Interactions between risks are crucial to consider because a specific response to a specific risk may enhance resistance to one damaging agent while increasing susceptibility to other causes of damage (Jactel et al., 2009). A global vision also allows diversifying the portfolio of mitigation measures and reducing the overall residual risk for forest economies (Birot, 2002). Furthermore, one of the key outputs of such integrated risk management approaches is to understand and combine the desires and beliefs from all stakeholders under external constraints (Yousefpour et al., 2013, Blennow et al., 2014). As highlighted by previous SWOT analyses, storm damage management is characterized by a high level of complexity, which is exacerbated by the manifold stakeholders, economic goals and personal beliefs. Agreeing on a common strategy for storm damage management is thus very tricky. To tackle this major challenge, we suggest forest policy and decision-makers should take the plunge and turn from an individual to an integrated management of storm damage risk.

Integrated approaches aim to combine several disciplines and involve different stakeholders operating in their own sphere (or subsystems, see below) across different spatial and temporal scales (Figure 10). Within this framework, storm damage risk can be addressed specifically, provided interactions with other risks (i.e. risk of pests' outbreaks, fires or game damage) are kept in mind (Fermet-Quinet, 2013). By analogy with the Integrated Natural Resources Management (INRM) concept (see e.g. Lal et al., 2002, Sayer and Campbell, 2002), an Integrated Storm Damage Management (ISDM) methodology should thus be built. Nevertheless, because integrated approaches are embracing, by definition, many topics in the same time, decision-makers need methodological supports to handle this complexity. The main requirements for applying an integrated framework are generally considered twofold: on the one hand to incorporate stakeholders requirements; on the other hand to provide decision-support methodologies (Lal et al., 2002).

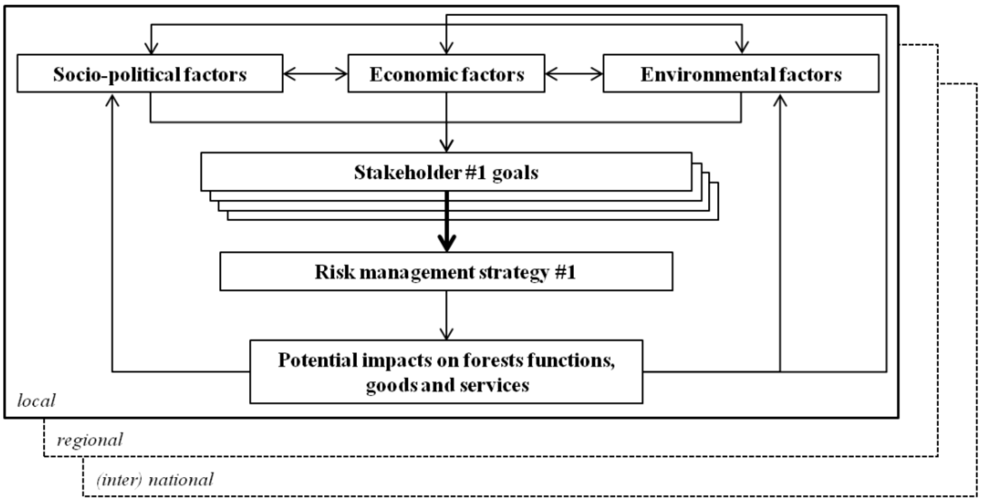


Figure 10. Generic framework for implementing integrated storm damage management (ISDM) approach (adapted from Campbell et al. 2002)

Regarding stakeholders targets, there is no simple method for balancing different concerns when facing scattered situations (Aven, 2009). The holistic approach proposed by Aven and Kristensen (2005) considers risk in its full dimension, taking into account possible consequences and associated uncertainties. An output-oriented approach (Greiving et al., 2012) could also help to determine "agreements on objectives" among stakeholders. In this latter approach, dialogue among experts, stakeholders, and decision-makers is fundamental in order to guarantee inclusion of all perspectives (values, opinions, and claims) in the risk analysis process. According to Greiving et al. (2012), a win-win situation among involved stakeholders could emerge with regard to reaching an agreement on common goals, and actions to achieve them in due course. Furthermore, participatory approaches could facilitate stakeholders' involvement in the decision-making processes (Ananda and Herath, 2003b), and increase the quality of decisions (Beierle, 2002). This is mainly relevant to multi-stakeholders decision-making processes (Garcia-Gonzalo et al., 2013) in which the willingness to share strategic information is a key factor of success (Marques et al., 2013a). For natural risks, when uncertainty in the decisions made is coupled with a high degree of conflict among the affected interest groups, combining participatory planning and structuring instruments like multi-criteria decision analysis methods (Mendoza and Martins, 2006) could serve to incorporate stakeholders risk preferences for policy-building (Gamper and Turcanu, 2009). Previous approaches to reaching common goals about risk management are promising and should be applied in integrated storm damage management. However, the success of an integrated storm damage management strategy will also lie in the ability to identify balanced strategies at an aggregated level of decision.

3.3.2. Towards systemic approaches

In order to support ISDM process and identify, in the portfolio of potential crisis measures, the most efficient way to reach mid and long term collective targets, we suggest a systemic approach should be used. Indeed, the complexity of storm damage management can be handled by using *Systems Theory*, since it can be conceptualized in a systemic way. In *Systems Theory* – also known as *Systems Thinking* – the complexity of these kind of systems can be considered and their dynamics – the interaction between elements – can be observed through simulations (de Rosnay, 1997). According to that, systemic analysis can be used to identify, optimize and control the system, while taking in account multiple objectives, constraints and resources (Heylighen and Joslyn, 1992). Systemic analysis is thus a powerful tool for specifying different storm damage mitigation scenarios, together with their associated risks, costs and benefits. However, it requests to determine first the scale, boundaries, inputs, outputs, and internal processes of the system in stake.

Scaling issues are crucial as the strategy might be assessed as being negative at one scale but positive at another (Sayer and Campbell, 2002). The analytic scale could also restrict the generality and utility of findings (Lovell et al., 2002). Regarding storm damage management, there is no unique appropriate level to judge the overall benefits of a strategy; therefore several systemic scales can be considered, according to the decisional level (supranational, national or regional) or management level (strategic, tactical or operational). Whatever the scale considered, it is fundamental to conceptualize the system and its relationships with sub- or meta-systems and remind that decisions at this specific scale can also influence those other systems. Example of a basic system including a succession of forest operations (salvage logging, transport, storage, processing), partially bound up with and affected by up- and downstream decisions as well as by the external context is given in Figure 11. In this example, the system encompasses successive steps of regional forest-wood chains and is thus composed by several sub-systems (Riguelle et al., 2015a). Its behaviour is influenced by regional, national and supranational (European) factors. Those external constraints may include political, institutional, financial, environmental, ideological, or social considerations that directly influence the state of the system.

The systemic approach was already suggested by Blennow and Sallnäs (2005) for active risk management in forestry. In their view, the forest-based sector is a wide system whose functioning is influenced by individual behaviours, and which interacts with elements outside of the system (Blennow and Sallnäs, 2005). Systemic approaches were also used to analyze the impacts of policy reforms on forest-based sector (Rametsteiner and Weiss, 2006a) or to study innovation in the forest sector (Rametsteiner and Weiss, 2006b). Regarding storm damage management, Systems Thinking concept is also partially applied nowadays. In fact, the first reaction after the storm is to determine if the event is expected to have critical (regional) or limited (localized) impacts on the forest-based sector. Former experiences usually help to determine threshold values, expressed in terms of resources impacted by the storm, beyond which the functioning of forest-based sector will be disrupted (Nieuwenhuis and O'connor, 2001a) and crisis management should be activated. Traditionally, the initial amount of damage is associated with an expected impact on the timber market and mobilization by comparison to previous windthrow crises.

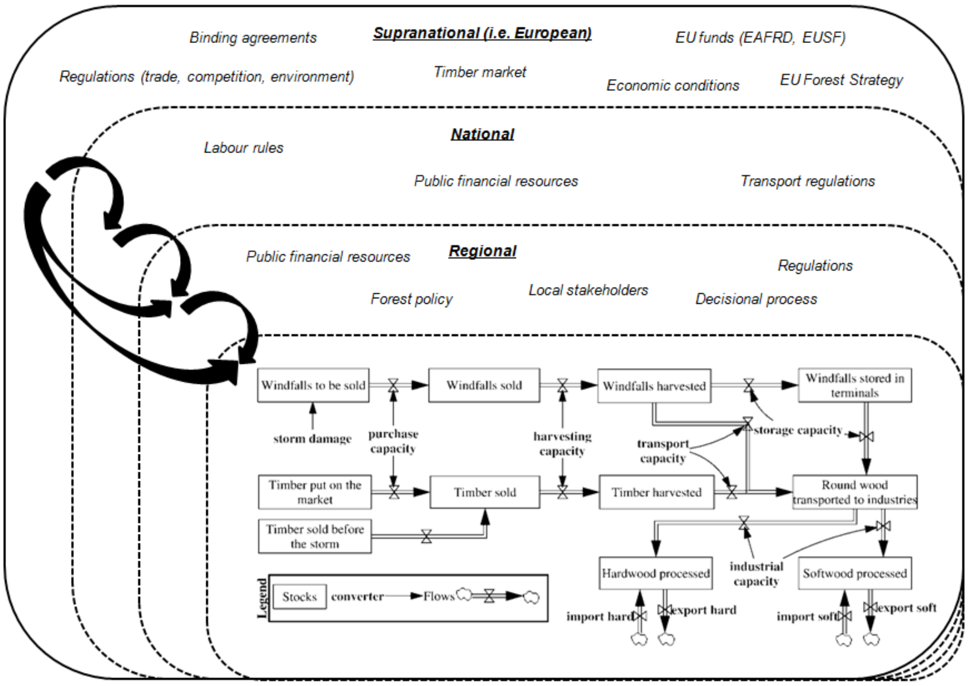


Figure 11. Systemic representation of a regional forest-wood chain. In this example, scale, boundaries (dash lines), inputs, outputs, internal processes and external drivers of the system are represented

This kind of systemic reasoning is valuable but oversimplified because it does not take into account the ability of the system to withstand the shockwave. In fact, damage threshold values could evolve between two critical events, due to internal changes within the system – resulting from active risk mitigation processes –, or external constraints. Thus in a second phase, deepen systemic analysis would still be needed to depict how the functioning of forest-wood chains will change according to a brutal disruption, where the bottlenecks are, and what the consequences will be of strategic action or inaction. Another premise is that within this system, which is a connected network, any individual element will not be able to reach its optimum state if others struggle with the crisis consequences. In other words, the global result is curbed by the weakest link in the chain. From that assumption, it follows that managing storm damage with a systemic approach will improve well-being at the aggregate level, and then could be profitable for each individual. While it does not exclude taking tailored measures with a limited scope to improve the functioning of a specific sub-system (i.e. logging or transport operations) or supporting stakeholders experiencing heavier storm impacts, it compels decision-holders to think globally. Even though the emergence of lone-rangers, who will acquire huge benefits from a crisis situation at the expense of others, is not excluded with this approach, it can be minimized if the crisis management strategy is balanced and the cooperation thereby enhanced (Fischbacher and Gächter, 2010).

3.3.3. Risk mitigation at the systemic level

Dealing actively with storm damage risk implies the definition of mitigation strategies based on the level of risk and the risk preference of decision-makers (Gardiner and Quine, 2000). At the individual level, each actor can choose between a set of measures to reduce, spread or manage the consequences of windstorms on his/her business (see Figure 12). Adaptation and mitigation strategies are well described, especially in regards to forest management (Heinonen et al., 2009, Schelhaas et al., 2010, Lagergren et al., 2012, O'Hara and Ramage, 2013, Subramanian et al., 2015). However, the sum of individual strategies does not guarantee the effectiveness of the global strategy, and systemic mitigation measures should be taken as complementary to them. Figure 12 presents some of the most relevant ways to increase both systemic resistance and resilience according to the risk-acceptance level of decision-makers.

The resistance of the system can be defined as its ability to function at close to its normal capacity and to carry on normal operations with minimal disruption after the storm. Resistance could be improved by reducing either the vulnerability or the exposure of the forest-based sector (FBS) at the regional scale (Figure 12). As mentioned in the previous sections, cohesion among stakeholders is a priority to reduce vulnerability. Another major opportunity to improve systemic resistance is to identify bottlenecks and find the way to address or avoid them before the next crisis. Bottlenecks are the weakest links of a system, therefore they are good indicators of its viability (Bossel, 2002). Practically, legislative, technical or financial hindrances may be the cause systemic dysfunctions. However, advanced modelling tools are necessary to lead systemic analysis and identify bottlenecks. From a systemic perspective, increasing the local demand for wood products could facilitate the absorption of damaged timber and lower the pressure on timber market. It could also contribute partially to a better regulation of the forest growing stock at the regional level, which is a major determinant of the level of damage (Usbeck et al., 2010). More generally, integrating risks in forest policies will have a positive impact on national resistance towards unexpected events (Blennow, 2008).

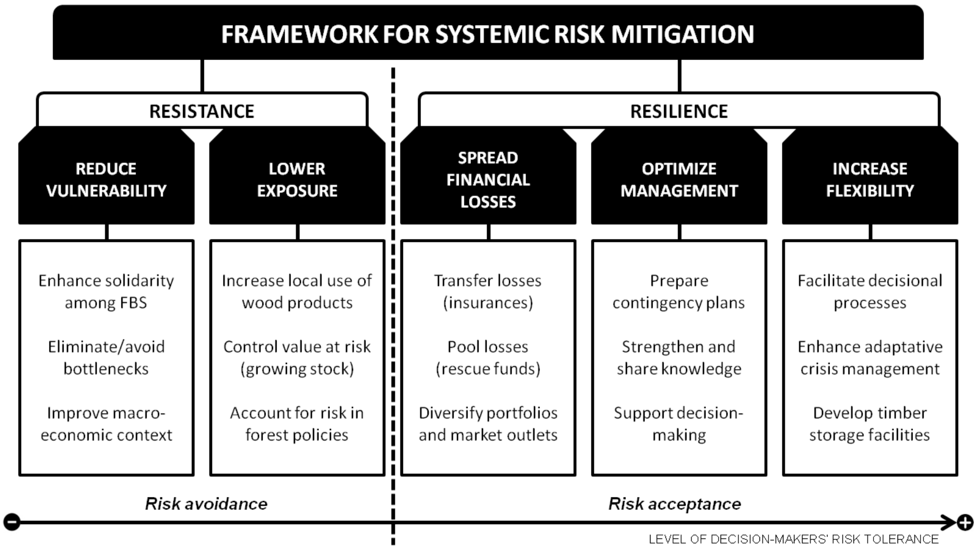


Figure 12. Set of strategies to mitigate impacts of storms on the forest sector at the systemic level

The resilience of the system is its ability to absorb a shock wave in such a way that it can return to a normal state with the least possible delay and with the least possible dysfunction (IPPC, 2012, Dymond et al., 2015). Ensuring decision-makers have a high level of information and preparedness corresponds with the enhancement of this systemic resilience. For these purposes, technical handbooks and contingency plans are key elements. Contingency plans are required to quicken and coordinate the operational and strategic response. Contingency plans developed in recent years for the public authorities (Bartet and Mortier, 2002, OFEV, 2008, Riguelle, 2010, Forestry Commission Scotland, 2014, Chtioui et al., 2015) or by the forest-based sector (Lesgourgues and Drouineau, 2009, FIBOIS, 2010a) illustrate how windthrow crises management may be optimized. Technical guides, as presented in chapter 2, also facilitate decision-making after the storm. Another option to increase resilience is to improve the flexibility of the system.

Past events showed that too rigid decisional frameworks and administrative procedures (Lesbats, 2002) as well as uncontrolled ideological issues (Raetz, 2004), may slow down the recovery after destructive storms. Yet this must not be underestimated in the systemic approach. The development of timber storage facilities which can contribute to softening the stumpage prices' variation (Costa and Ibanez, 2005) is also a main option for improving systemic resilience.

Between these two options, a possible middle path is to spread the risk. A possibility is to transfer the financial consequences of storms from one party to another. Compensating losses through insurance is an option for the forest-based sector (Birot and Gollier, 2001) but its implementation is slowed down by several issues (Brunette et al., 2015b), including the belief that public subsidies will always compensate the losses (Brunette and Couture, 2008). Indeed, public authorities used to build rescue funds to pool the risk or mobilize extra budgets to provide financial compensation for storm damage, and these safety nets may have reduced the sector's willingness to purchase insurance or invest in risk reduction (Brunette and Couture, 2008). Insurability of natural hazards in forestry has already been identified as a prerequisite for risk mitigation (Birot and Gollier, 2001) but with limited response from both public authorities and insurers in some countries. Nowadays, the forest-based sector needs clear public commitment about assurance premiums, incentive programs, and self-insurability (Sauter et al.).

3.3.4. Assessing systemic impacts of storms

Taking decisions according to this integrated and systemic framework is not easy for decision-makers, as they have to consider simultaneously internal interactions between stakeholders, and influences from the external context. It implies continuously gathering information during the decision-making process and identifying barriers or distortions that arise from decisions or the absence of decisions. To a certain extent, technical handbooks already bring knowledge-based decisional support to decision-makers and can drive decision-making processes. In addition, decision-makers may request aggregated information and calibrate mitigation strategies at the global level. A main requirement to address systemic issues is to provide to decision-makers a deeper understanding about economic knock-on effects of storms. In order to identify expected changes and key levers before windthrow crises, it is recommended that the long-term effects of policy options and economic context on the forest-based sector are assessed as, for instance, Schwarzbauer et al. (2013) did with a dynamic system model for the Austrian forest sector. Outside the crisis period, mapping the wood harvesting changes, which result from the salvage harvesting that follows destructive storms at an aggregated level (Verkerk et al., 2015), could serve to assess potential economic losses. During the crisis period, from a purely economic angle, the challenge will be to manage stocks in order to smooth fluctuations and, for this purpose, it is necessary to understand how the wood markets react to disturbances (Baur et al., 2004). A model of timber market dynamics after natural catastrophes was also used by Prestemon and Holmes (2004) to explore how U.S. government spending to mitigate economic losses through timber salvage is related to the costs of intervention This simulation model illustrates how such an approach could, in time, support crisis response and a cash-constrained context (Prestemon and Holmes, 2004).

Including the economic dimensions of disturbances in the decision-making processes is a core requirement (Holmes et al., 2008). First, a thorough understanding of overall economic impacts of wind hazards, including damage and risk mitigation costs is required (Meyer et al., 2013). Assessment of storm economic impacts begins with sound damage assessment procedures at the regional or national level, which is mandatory within the first days to support decision-making (Honkavaara et al., 2013). Whatever the methodology chosen at regional scale (field inventory, aerial, or satellite imagery) estimates, which imply a trade-off between accuracy and swiftness, must only be used to calibrate the crisis response (Riguelle et al., 2011). Indeed, inferring systemic economic impacts from the initial amount of damage is misleading as secondary and tertiary damage are not taken in account, nor are the benefits of mitigation strategies. For example, secondary damage resulting from bark beetles outbreaks in the follow-up to large disturbances (Wermelinger et al., 2002) are responsible, on average, for extra damage of between 10 and 25% of initial wind damage (Stadelmann et al., 2013). Thom et al. (2013) demonstrated that for every cubic meter of bark beetle damage in the current year, 0.56 m^3 of additional bark beetle damage is expected in the following year. This not only means that sanitary concerns must be integrated as soon as possible in the decision-making scheme (Wermelinger et al., 2013), but it emphasizes the need for an advanced cost-benefit analysis to inform decisions. For example, it could be useful to assess the need to make salvage cuttings in partially damage stands in regards to the potential secondary losses (Stadelmann et al., 2013).

Economic assessments also implies quantifying in monetary terms the public benefits and externalities generated from forests' goods and services (Buttoud, 2000). As an illustration, destructive storms in forests can cause a huge reduction of carbon sinks (Lindroth et al., 2009) that would have been far more costly if created in other ways (Canadell and Raupach, 2008). Therefore, they can cause additional losses for owners if they have to repay emissions units (Moore et al., 2013). Such considerations must be included in decision-making processes. Nonetheless, assessing the economic effects of disturbances requires models with a considerable scope (Toppinen and Kuuluvainen, 2010). For example, modelling the forest-based sector as a group of interacting autonomous economic agents would make possible analyzing the effects of forest-based disturbances on market dynamics (Schwab et al., 2009). In the ex-post evaluation of the French state's compensation plan after hurricane Klaus (Bavard et al., 2013), a bio-economic partial equilibrium model (Caurla et al., 2010) was used to compare a set of alternative management scenarios through varying output variables, such as prices and timber volume. This approach is very promising for supporting strategic decision-making, for example, to assess alternative strategies for timber export and storage (Caurla et al., 2015). In this context, a main challenge is to improve the reporting of economic data to help ex-post assessments and build models to predict the economic impact of storms on both individual agents and the forest-based sector as a whole.

3.3.5. Supporting systemic decision-making

Those challenges also emphasize the need for a portfolio of decision support systems (DSS) where decision-makers can find appropriate tips. An illustration of how system analysis can drive the strategic management of storm damage is presented below. In this example, taking place in Wallonia (Belgium), a decision-support system based on System Dynamics principle, the WIND-STORM software (Riguelle et al., 2015a), is used to predict how transport capacity and timber storage may influence the amount of timber laying on forests areas and industrial log yards during a five-year period after a destructive storm. Four scenarios have been simulated, on the basis of an overall damage of 8 million cubic meters: a baseline scenario, for which no specific measure is taken after the storm (BASE); a second scenario where only the harvesting capacity is boosted by 20 % (SC1); a third in which both harvesting and transport capacities are increased by 20 % (SC2); and a fourth where 2 million cubic meters of damaged timber are stored during 24 months (SC3).

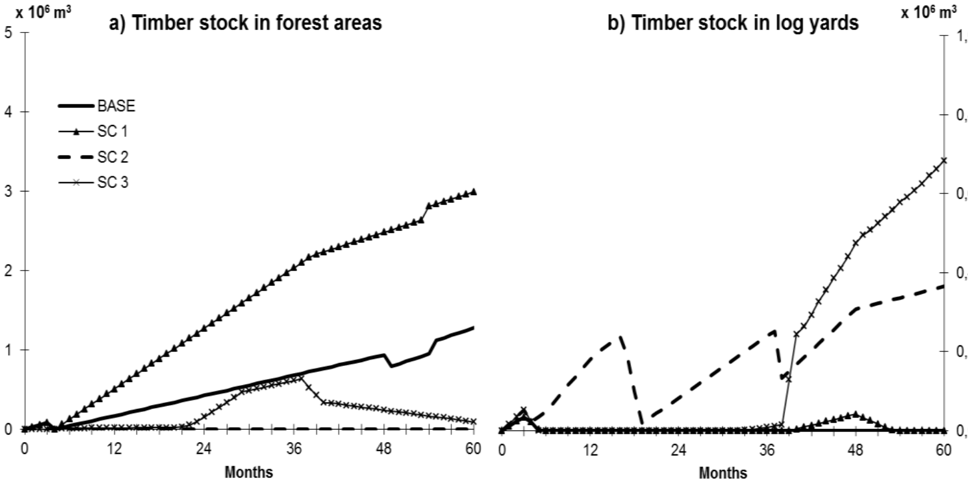


Figure 13. Example of systemic analysis supporting strategic decision after windstorms. (a) Stock of timber in forest areas; (b) Stock of timber in forest areas

Simulations show that transport capacity is lacking even in the baseline scenario and is therefore a systemic bottleneck (Figure 13a – BASE). As transport capacity is a limiting factor, efforts to improve salvage logging have a limited impact as the harvested timber is progressively accumulating in the forest areas (Figure 13a – SC1), which increases the risk of secondary damage. Doubling the transport capacity can nullify the stock in forests, but it causes accumulation of timber in log yards (Figure 13 – SC2). Timber storage is able to alleviate the accumulation of harvested wood in forests and preserve it from decay; however, as seen in Figure 13b, too rapid destocking can cause an excessive supply if no measures to limit the upstream offer are taken. Interested readers should refer to (Riguelle et al., 2015a) for a thorough description of this type of DSS and its contribution to systemic analysis.

3.4. RECOMMENDATIONS TO PUBLIC AUTHORITIES

This paper also offers an opportunity to highlight some of the main challenges for public authorities in supporting forest-based sector in the context of integrated storm damage management. According to Figure 11, public authorities could play an active role and beyond, they should be the catalysts of this process. Five key challenges are briefly discussed:

- Improving public risk governance and awareness;
- Developing an integrated policy for forests risk management;
- Enhancing systemic resilience of the forest-based sector;
- Facilitating the implementation of decisions;
- Playing an active role in windthrow crisis management.

Improving public risk governance and crisis management awareness is a prerequisite to be ready to cope with exceptional events (Mortier and Bartet, 2004). Solutions to promote a risk awareness culture within public organizations could involve making knowledge of risk management issues a selection criterion when recruiting high-level officials, conducting risk surveys and audits, providing trainings and workshops to the staff, and organizing frequent crisis exercises. Moreover, the need for integrated policy of forest risk management is not only a challenge for the forest-based sector, but also for the public authorities. They must provide the guidelines according to which the forest sector develops its own strategy. For example, they must clearly indicate what losses the policy will cover in case of damage. The challenge is to find the optimal share between public and private compensation (Nicolas, 2009). Some governments used to undertake large interventions; nowadays, direct financial support to the forest-based sector is likely to be restricted by the EU's competition law. In addition, public compensation after windstorms may be counterproductive assuming it curbs stakeholders investing in risk-reducing options at the individual level (Brunette and Couture, 2008). On the other hand, insurances that could help to alleviate pressures for public compensation in the aftermath of natural disasters (European Commission, 2013b) are not widespread in the forest sector. Whether there is any ideal framework to share the economic risk due to various forest ownership patterns and habits, the forest-based sector requires a clear view on what they can expect back from public authorities if they subscribe to insurance or self-insurance programs.

Public authorities should also take initiatives to improve the systemic resistance and resilience of the forest-based sector. Whether they have any direct influence on the macro-economic context, they can act locally by alleviating the constraints with which the forest-based sector struggles. In parallel, they should identify institutional bottlenecks and try to resolve them in advance by leading on prospective systemic analyses (Riguelle et al., 2015a). The continuous improvement of the system also requires consistent and systematic ex-post evaluations of public policies (Bisang and Zimmermann, 2006).

In addition, public authorities should act to facilitate the effective implementation of decisions. This begins with a flexible decision-making context that can be adapted throughout the crisis period. It also means simplifying administrative processes and ensuring that all the stakeholders within the decision-making chains, not only the forest agencies, are aware of their role (Raetz, 2004). For instance, ministerial orders or authorizations that are not issued on time have slowed down recovery in the past (Lesbats, 2002, Nicolas, 2009). The public authorities must also communicate on their strategy, the choices made, and the underlying long-term vision to facilitate the acceptance and the implementation of their strategy (Bavard et al., 2013).

Finally, public authorities should invest money and human resources actively in windthrow crises management in order to ease the implementation of strategic decisions. On the one hand, they should set up contingency plans and improve then continuously following “Plan-Do-Check-Act” principle. On the other hand, public authorities could play a crucial role in regulating the timber market, for instance by mutualizing timber sales to stabilize stumpage prices. To be effective, forest agencies should be first in line to support market facilities, by reducing the public timber offer or postponing payment delays, for instance. The main operational challenge for public authorities is to anticipate and prepare timber storage operations (Bavard et al., 2013, Birot and Gardiner, 2013). This implies, among other things, identifying potential storage areas and developing a mutualized management framework to pool the costs and limit the fees for public and private owners.

3.5. DISCUSSION

In this chapter, several sources of information were combined to draw a global picture of current issues and opportunities concerning strategic decision-making and management of storm damage. We reached a conclusion that the forest-based sector has quite often a good perception of the windthrow phenomenon and is able to handle rapidly its consequences, owing to a strong empirical knowledge. Saving and sharing this knowledge, through contingency plans for instance, is essential, even more in countries that did not experience storm damage since decades. However, storm damage risk management cannot rely only on former crises, since the decisional context is changing and uncertain. Upcoming threats and opportunities arising from this uncertain context must be considered in the decisional process, as they will influence the way to deal with storm-related issues in the future. A way to reduce uncertainty in the aftermath of storms is to strengthen the resilience and resistance of the forest-base sector towards destructive storms, by addressing main issues highlighted in this paper. Although some of these issues have already been addressed in some countries, this review can contribute to re-open the debate in order to foster the implementation of good practices and bridge remaining gaps at regional and national levels. Nevertheless, insofar as it is unrealistic to deliver a tailored solution for storm damage management, new approaches that could help to reduce the global impact of storm crises are also needed.

One way to deal with complexity and uncertainty throughout the risk management process would be to change perspectives and adopt an integrated management of storm risks, ideally as part of a wider analysis of forests' risks that could help to handle the multiplicity of risks coherently. However, because integrated approaches are embracing many concepts, two prerequisites are highlighted: firstly, the forest community needs to develop advanced methodologies to deal with such complex issues and, on the other hand, dialogue among and outside the forest community must be enhanced. According to that, a systemic approach for storm damage management is also suggested in this paper to deal with the forest-based sector as a dynamic system. This holistic approach assumes that the strategy will not be optimal if some individuals are suffering from crisis conditions within the system. In contrast, a balanced solution for the whole sector will likely benefit all stakeholders individually. The resulting idea is to evaluate all possible mitigation scenarios through a systemic perspective, with the help of appropriate decision support systems. This approach requests, however, identifying the scope (regional, national or supranational) and the internal and external drivers of the system in stake.

Finally, we insist on the role of public authorities in supporting windthrow crisis management at the European, national and regional levels. On the one hand, public decision-makers should foster the development of an integrated policy about forest risks and take part more actively in the storm damage management process. Nevertheless, such active involvement requires enhancing risk culture within politics and public bodies. Furthermore, it is also crucial to ensure the mobilization of decision-holders (ministers and high-level officials), and not only the institutional players. On the other hand, high transparency in public policy- and decision-making processes is needed to build confidence between the forest community and public authorities. Public authorities should also be the drivers for enhancing cooperation and reducing competition between bordering countries, which remains a major impediment in post-storm crisis periods. In regards to this challenge, the European Forest Strategy (European Commission, 2013a) targets to enhance cooperation between member states and facilitate the coherence of forest-related policies in Europe, whereas the building of an European Forest Risk Facility (Landmann et al., 2015) illustrates that the forest community actively concurs with the need for a better collaboration between stakeholders inside the forest sector and with decision-makers.

Second section

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Supporting risk management and decision-making

- Regarding their severity and occurrence, risks associated to huge storms are often too high to be tolerable as such by public and private decision-makers. In addition, limiting the exposure and vulnerability of forests towards wind damage can be costly and ineffective when considering high wind speeds.

- An option for decision-makers is thus preparing themselves to face and response to the storm outcomes by developing a crisis management strategy. However, this strategy must be supported by sound decision-making processes and institutionalized in contingency plans.

- In this context, we developed a model for assessing systemic risks within the forest-based sector and supporting decision-making during risk management process. In accordance with the risk governance approach, the tool also resorts to participatory processes for improving quality of decisions, and it can also serve for pre-assessing risks and solve systemic bottlenecks.

- In addition, contingency plans can be established by risk and crisis managers to reduce impacts of sudden disasters on forest-related activities by enhancing preparedness and response to windthrow crises. Chapter 5 presents the main feature of the contingency plan developed in the course of this thesis for public forest sector in Wallonia (Belgium).

4 STRATEGIC DECISION-MAKING

This chapter addresses decision-making issues that arise during storm damage management. More particularly, we focused on decisions that frame the strategy of public authorities in the aftermath of storms. The output of our research is modelling software that can be used as a Decision-Support System (DSS) by public authorities either for crisis management or preventive risk assessment.

This chapter is a transcription of the following paper:

> RIGUELLE, S., HÉBERT, J. & JOUREZ, B. 2015. WIND-STORM: A decision support system for the strategic management of windthrow crises by the forest community. *Forests,* 6**,** 3412-3432.

4.1. INTRODUCTION

Windstorms are one of the most damaging agents for forests in the Northern Hemisphere, especially in Western Europe (Schelhaas et al., 2003). These natural disasters have significant social and environmental impacts (Gardiner et al., 2010) and inflict huge economic losses on the forest sector (Hanewinkel and Peyron, 2013). Impacts on the forest-based economy of exceptional events that blow down at least the annual average harvest at the industrial supply scale can last a couple of years (Peyron, 2002). Storms directly impact both timber production and timber prices (Brunette et al., 2012), as forest owners are tempted to harvest to limit financial losses. This afflux of timber on the market combined with a poorer quality of fallen timber and the increasing costs of salvaging contribute to lower stumpage prices and inflict revenue losses on forest owners (Prestemon and Holmes, 2004), who are also suffering from future revenue losses due to an anticipated harvest of non-mature stands (Nieuwenhuis and O'Connor, 2001b). The industry as a whole will also be affected, with the main impact being on roundwood prices and procurement in the mid to long term. After a storm event, there is a short-term increase in the wood supply, usually followed in the medium term by a supply shortage if no mitigation measures are taken (Schwarzbauer and Rauch, 2013). A storm event will also cause operational difficulties resulting from the lack of harvesting and transport capacities (e.g., working force, harvesters, and trucks), which may slow windfall mobilization and storage operations.

These factors show how important it is that public authorities ensure post-storm crisis management to minimize the short-, mid-, and long-term economic, social, and environmental impacts on the forest-based sector. Public authorities such as governments and public bodies are the key players in the crisis management process for three main reasons: first, they act at the legislative and decisional levels to facilitate or promote crisis measures; second, they can mobilize financial resources to support the forest-based sector; finally, they are the central point of contact for forest-based sector stakeholders. Given current scarce public resources; however, their first priority is adopting the most efficient crisis measures to provide return on public investments. Given the strong interrelation among actors in the forest-based sector, they must not only consider the measures' efficiency on an individual basis but also pursue the global improvement of the system. These tasks require setting up support tools in order to improve strategic decision-making.

One general way to support decision-making is to use models included in decision support systems (DSSs) to make them more accessible to end-users. Most of the DSSs used in forest management are model-based (Packalen et al., 2013, Segura et al., 2014). Models are also frequently used in forest economics to simulate situations that may result from changes in policy (e.g., new subsidies, tax systems), market conditions (Wibe, 2005), or climatic conditions (Hanewinkel et al., 2013). Among these models, some are general equilibrium models, in which the forest sector interacts with other sectors of the economy (Sohngen et al., 2001, Ochuodho and Lantz, 2014). Models in which only the forest sector is analyzed, ignoring interactions with other economic sectors, are considered partial equilibrium models. The model scope may vary, from local to international scale—the latter including the interrelations among national forest sectors. For example, the Global Forest Products Model (GFPM) described by Buongiorno et al. (2003) can be used to simulate how timber production and the harvesting, manufacturing and transportation of products in various countries interact through international trade.

Model applications to forest-wood chain management are various: they include demand and procurement (Kong et al., 2012), harvest planning (Karlsson et al., 2004), productivity of harvesting operations (Murphy and Vanderberg, 2007, Spinelli et al., 2010), and transportation planning (Forsberg et al., 2005, Carlgren et al., 2006, Frisk et al., 2010). Models are also frequently used in operational research to support industry and organizations in forest-wood chain planning (Weintraub and Romero, 2006, D'Amours et al., 2008, Chesneau et al., 2012, Palander and Voutilainen, 2013), after the storm Gudrun in Sweden for instance (Broman et al., 2009). However, no DSS has been proposed to support systemic analysis and strategic management of storm damage and associated impacts on the forest-based sector after storm events.

Therefore, this paper presents an original DSS to assist post-storm crisis management and support public authorities' decision-making in the aftermath of huge storms. The DSS' expected output is a comparison of changes in the dynamics of the regional forest-based sector after storms under different crisis management options. The DSS is based on a regional forest model (WALFORM) developed for a case study of Wallonia, the southern region of Belgium. The first chapter describes the development, implementation, and calibration of the model. The second presents an application of the model-based DSS WIND-STORM to a hypothetical storm crisis. Finally, a discussion and conclusions highlight the pros and cons of using this DSS for storm crisis management.

4.2. THE REGIONAL FOREST MODEL (WALFORM)

4.2.1. Conceptualisation

This model represents the regional forest-wood chain dynamics after a storm event. The system dynamics is modelled in terms of stocks, representing the state of the system at any given moment after the storm, and flows, representing the rate at which these stocks are changing at any given instant. System dynamics (Forrester, 1994) has been used to model the interactions between stocks and flows, as this quantitative modelling method enables the building of a simple representation of complex systems. It has been used in several studies on forestry (Buongiorno, 1996, Bousquet and Le Page, 2004, Collins et al., 2013, Schwarzbauer et al., 2013, Stern et al., 2015) and supply chain management (Mentzer et al., 2001). To identify the stocks, the regional forest-wood chain is considered to be the succession of several forest operations: wood purchase, harvesting operations in the forest stands, the transportation of logs and bolts outside forest areas (either to industry sites or to storage terminals), and their primary transformation by local industries for various uses (e.g., sawn timber, paper, panels, fuel wood).

Figure 14 presents a conceptual representation of WALFORM in terms of stocks and flows. The model consists of four interrelated subsystems: purchase, harvesting, transport (including storage), and industry modules. A distinction is made between windfalls, trees affected by wind damage (e.g., uprooted or broken trees), and timber, trees unaffected by the storm (either standing trees or wood products derived from them). For any moment t, input and output rates (flows) determine the level of windfalls and timber within each module (stocks). The rates correspond to the financial or technical capacities available to purchase, harvest, transport, store, or process windfalls and timber. Four groups are distinguished in the model, both for windfalls and timber (spruce, other softwoods, beech, and other hardwoods). For the industry module, groups of species are aggregated in two raw material types (softwood and hardwood species).

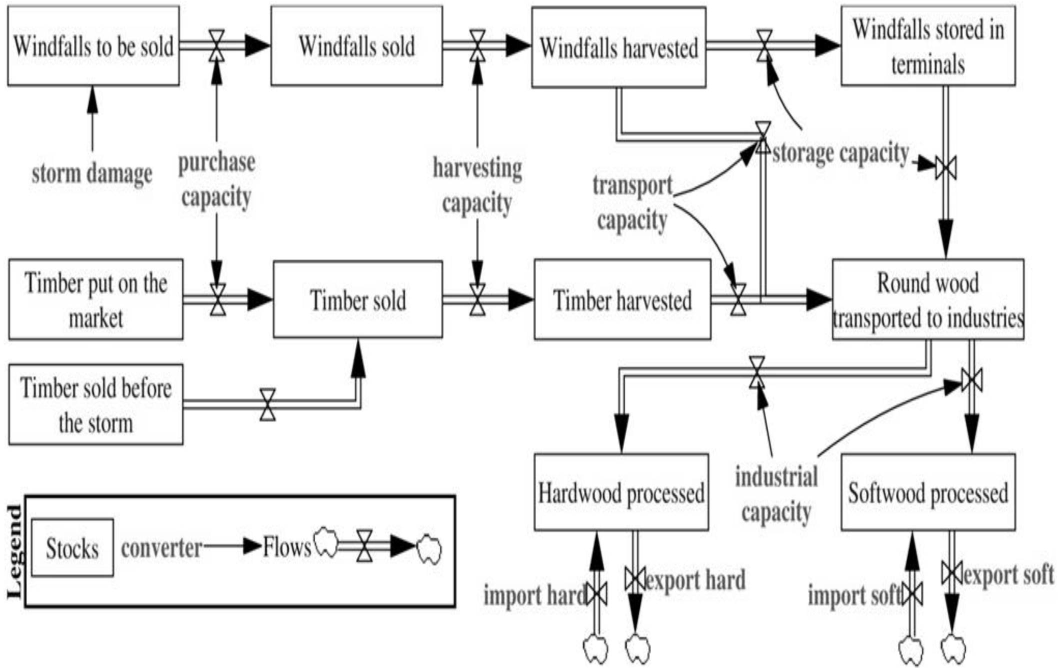

Figure 14. Conceptual representation of the regional forest-wood chain

The first step in building the model was selecting the parameters that influence the stocks and flows in a normal situation (*i.e.*, no storm damage); then, the parameters specific to windthrow crises were added. This selection occurred in close collaboration with stakeholders from the forest-based sector, using expert knowledge to sort the information. Particularly challenging was finding a way to reflect the range of storm damage management options implemented in the past, in both Belgium and elsewhere.

Figure 15 presents the WALFORM model derived from the previous conceptual representation using System Dynamics generic notations. Boxes represent stocks; hourglasses with double arrows represent flows (in italic and bold), and all other elements are converters. The model is composed of 13 stocks, 18 flows, and 61 converters (either constant or variable), as listed and described in the Table 13 (appendix). The simple arrows in Figure 15 represent the interactions between parameters. Blue arrows indicate a positive influence: the higher the initial converter is, the higher the impacted converter will be. Red arrows indicate a negative influence: the higher the initial converter is, the lower the impacted converter will be. Dashed arrows indicate that the converter determines only the initial value of a stock. Black arrows with delay marks indicate that a time delay may be applied to the targeted converter. For instance, the activation of payment delays (delay pay) may block or lower the associated converter (timb to pay) for a pre-determined period.

The WALFORM model is an open system: unlike feedback systems, it is not influenced by its past behaviour. The capacities (flows) are the only parameters that determine stock levels. However, the levels of stocks downstream from the system are a function of the upstream stocks; thus, the real value of flows will be the minimum between the capacities and the amount of wood (windfalls or timber) available in the stocks at that time. The mathematical relations between stocks and flows and between flows and converters are presented in the Table 14 (appendix). Euler integration is used to solve the equations. Due to the complexity of these relationships, the sections below will focus on the converters of the four modules and their positive or negative influence on the capacities.

4.2.2. Purchase Module

The purchase module (see Figure 16) depicts the dynamics of windfalls and timber sales. The two main inputs are the volume of damage and the standing timber put on the market. The amount of windfalls to be sold (WIND SALE) depends on the initial amount of the damage (damage) and the damage mobilization rate (dam mob), which reflects the proportion of windfalls inaccessible or economically unprofitable to harvest. In the case study on Wallonia, a quick damage assessment methodology enables an estimation of the amount of damage within 72 h to feed the model (Riguelle et al., 2009). The amount of timber put on the market (TIMB SALE) is a function of the annual repartition of sales (timb rep), of the average annual sales (vol timb norm), and of supply variation (offer).

The offer parameter reflects the willingness to put more or less timber on the market during the crisis period. It must be defined for each group of species and for separate periods of 12 months. It is an aggregated value, meaning that it reflects the average behaviour of public and private owners. The purchase capacity (pc tot) is the global financial capacity for buying wood, expressed in monetary terms. It is affected mainly by prices and demand (see annexes for mathematical relations). Prices after the storm are obtained by applying a devaluation rate (wind dev, timb dev) to the initial prices (price init), which are stumpage prices' mean current value for each group of species, obtained through statistical methods (Sanchez et al., 2004). Additional devaluation may be applied to windfalls from the second year (wind dev supp). The purchase capacity assigned to windfalls (*Pc wind*) and timber (*Pc timb*) is chosen by the user (pc ratio). The government may exceptionally authorize a deferred payment plan for a limited period in order to temporarily boost purchase capacity (pay delay); here, potential buyers benefit from higher financial capacities in the early months and are allowed to pay off the balance later. Increases and decreases in roundwood demand under economic constraints are also taken into account (demand). In the model, variations among imports (diff imp) directly affect purchase capacity, as reduced (increased) imports are thought to be compensated for by a higher (lower) demand for local resources. Regardless of purchase capacity, public authorities may foster exchanges between timber already bought and windfalls in order to redirect prior investments. This proportion will depend on the predetermined exchange rate (exch rate) and on the amount of timber sold before the storm (vol timb init) and not yet harvested.

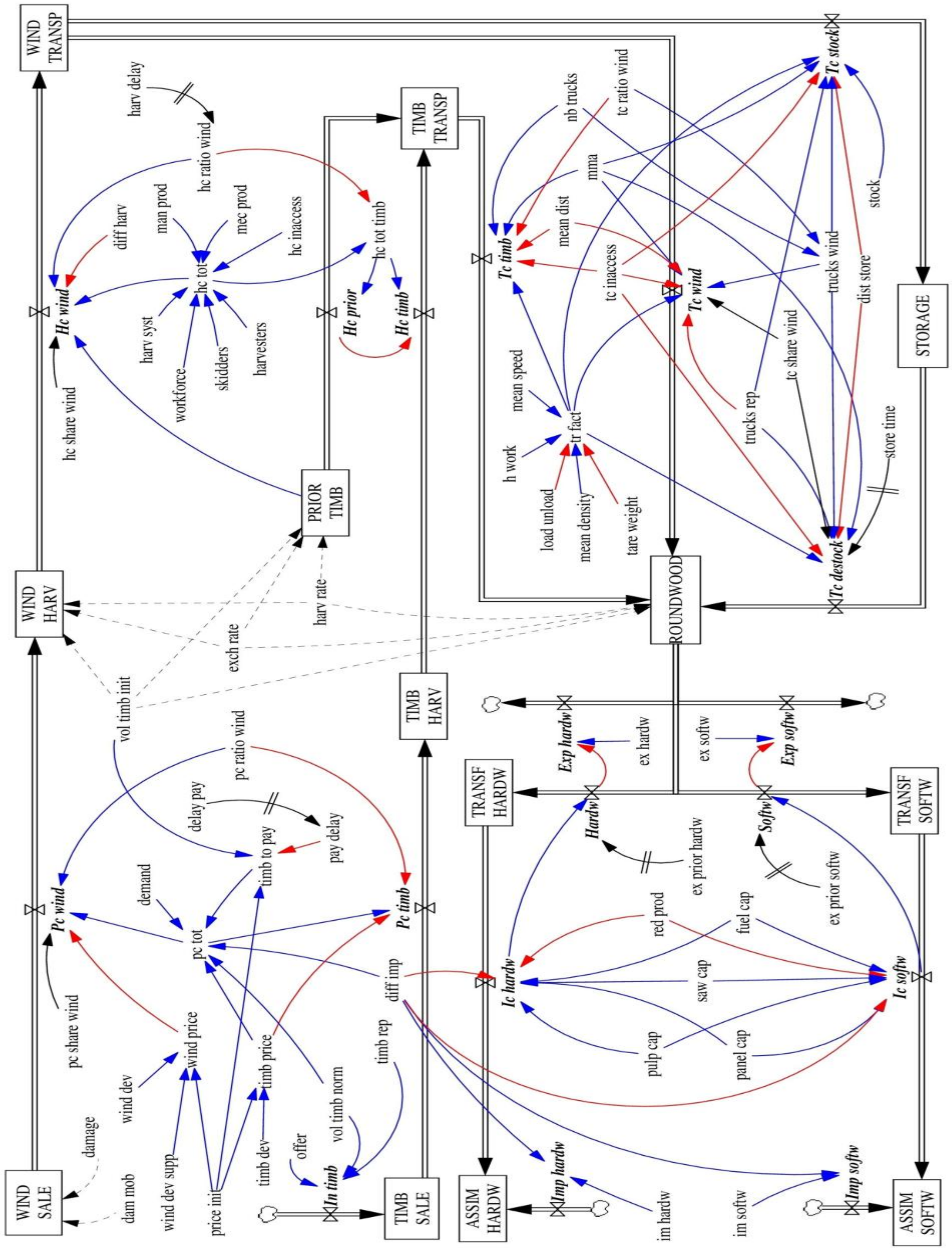

Figure 15. WALFORM model structure and parameters. Boxes represent stocks, double arrows with hourglasses flows (in italic and bold). Blue (red) arrows indicate a positive (negative) influence between converters. Dashed arrows indicate that the converter determines only the initial value of a stock. Black arrows with delay marks indicate that a time delay may be applied to the targeted converter.

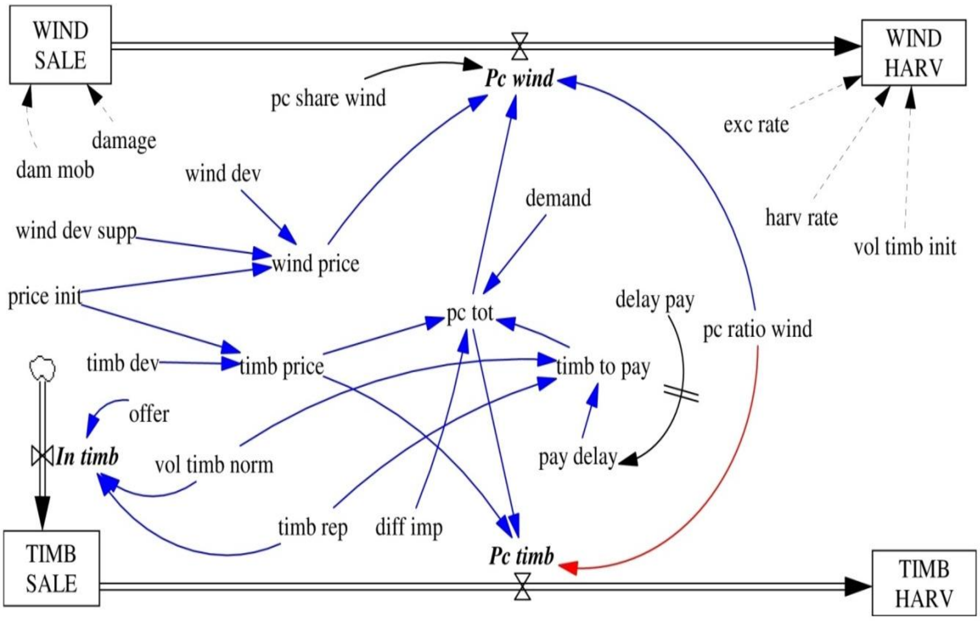

Figure 16. Purchase module

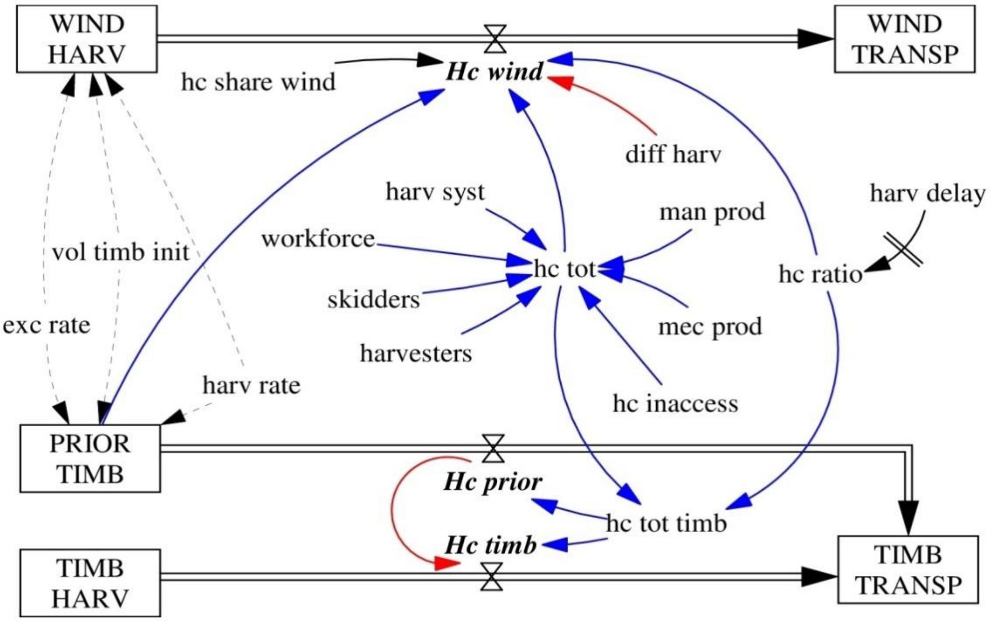

Figure 17. Harvesting module

4.2.3. Harvesting Module

The harvesting module (see Figure 17) focuses on the harvesting operations within the forest-wood chain. Upstream stocks are amounts of wood sold that must be harvested; downstream stocks are amounts of wood harvested that must be transported to either storage terminals or industrial sites. The volume to harvest in forest areas is still divided between windfalls and standing timber at this stage, as harvesting systems and productivity differ in both cases. The module also includes the amount of windfalls exchanged with timber and the timber sold before the storm (PRIOR TIMB). Again, public authorities may extend harvesting delays (harv delay) for a limited period to increase the windfalls harvesting rate.

Harvesting capacities relative to windfalls (*Hc wind*) and timber (*Hc timb*) are derived from the total harvesting capacity (hc tot). The overall capacity is a combination of several parameters: the available working force (workforce) and harvesters (harvesters), the manual and mechanical harvest productivity (mec prod, man prod), and the choice of harvesting systems (harv syst). For example, in damaged stands, mix-harvesting systems are frequently required to ease access through entwined trees. This global capacity is pooled and redistributed according to strategic choices (hc ratio). For windfalls, a reducing factor (diff harv) is applied to reflect the more difficult working conditions and the lower productivity in damaged areas. As in the purchase module, a specific distribution of harvesting capacity between each group of species may be simulated (hc share wind). For example, priority may be placed on harvesting the species with a lower natural durability first to prevent them from decaying.

4.2.4. Transport Module

The transport module (see Figure 18), focusing on the transportation of wood from forest areas to industrial sites or storage terminals, is a highly strategic link in the forest-wood chain. In this module, windfalls are again distinguished from timber products, under the hypothesis that there are no economic reasons to store undamaged timber on storage sites. However, the level of roundwood stock is the sum of windfalls and timber volumes brought to industrial sites. If storage is activated, the maximal amount to store (stock) and the minimal storage time (store time) must be defined. Transport from storage locations to industries will not be possible if the minimal storage time is not reached. Nevertheless, storage is an option and can be bypassed in the model.

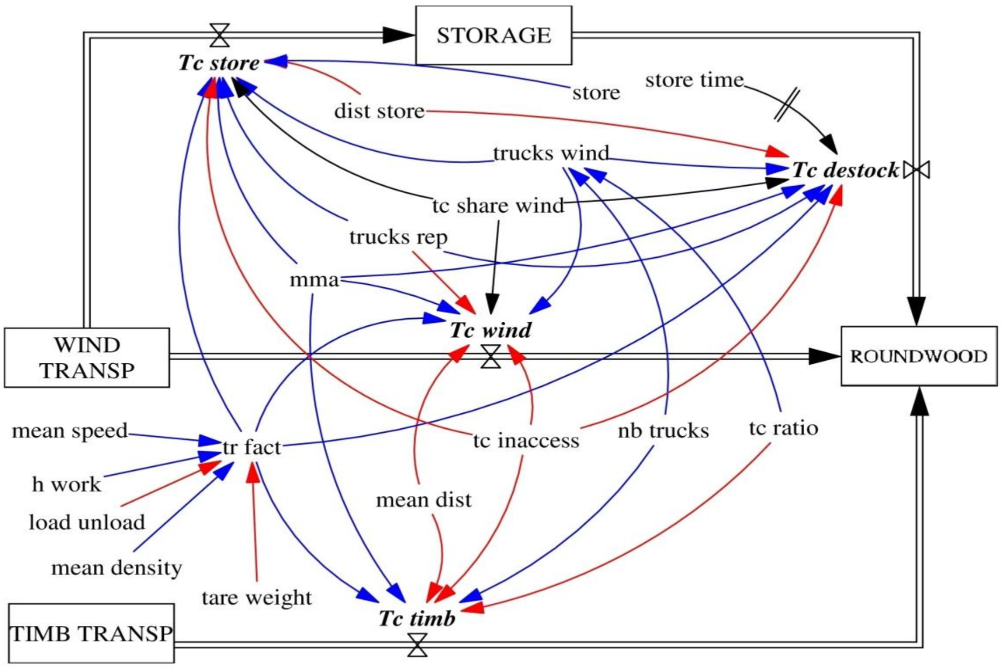

Figure 18. Transport module

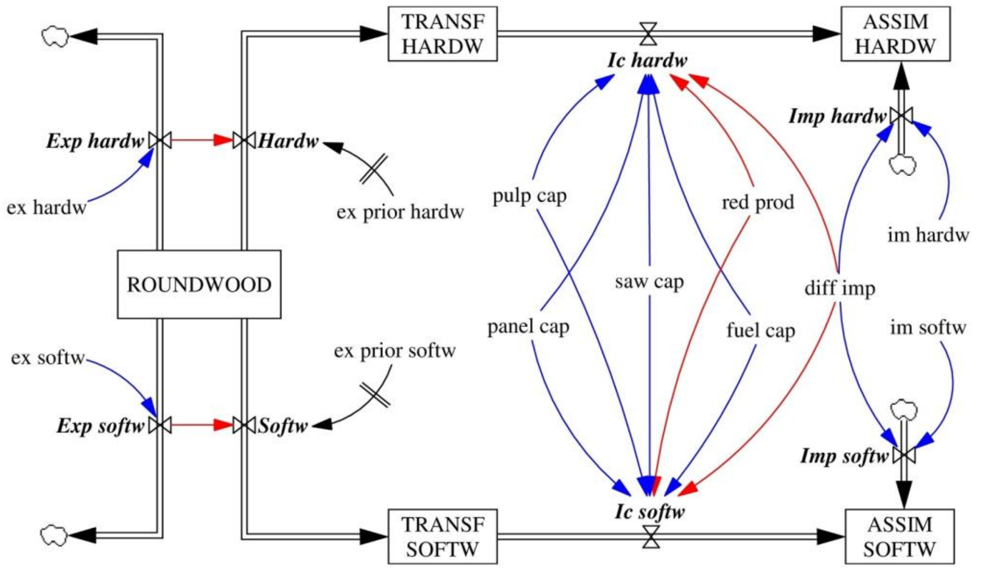

Figure 19. Industry module

The specific transport capacities (*Tc wind*, *Tc timb*, *Tc store*, *Tc destock*) are functions of several parameters: the number of trucks, the maximum mass authorized for the trucks (mma), the mean distance of transport from either forests to industries (mean dist) or forests to storage terminals (dist store), and the truck productivity factor (tr fact). The quantity of trucks available for each operation is predetermined by the user. All of these parameters must be determined for both normal and crisis situations, as specific authorizations may be delivered for limited periods to boost the transport capacity (e.g., to increase the maximum mass authorized for trucks or public incentives to resort to foreign haulers).

4.2.5. Industry Module

The industry module (see Figure 19) represents wood consumption by the primary timber industries (sawmills, paper mills, wood panel manufactures) and the fuel wood sector. In this step, the groups of species are aggregated into two types of raw material: softwood (including spruce and other softwood species) and hardwood (beech and other hardwood species). Exporting flows (*Exp hardw, Exp softw*) drain roundwood out of the system, while importation flows (*Imp hardw, Imp softw*) add volumes at the end of the process. Industrial capacities for hardwood (Ic hardw) and softwood (Ic softw) are obtained from specific sector capacities (saw cap, pulp cap, paper cap, fuel cap).

4.2.6. Implementation and Calibration

The model was implemented in Excel VBA (Visual Basic for Application 6.3). Excel software seems an appropriate trade-off among accessibility to a wide public, the possibility of designing user interfaces, the power of calculation, and programming interface. The model simulates a 60-month period after a storm event, with a time step of one month. It was calibrated for the regional forest-based sector of Wallonia with data collected through an intensive literature review and interviews with stakeholders. Given normal market conditions, without storm damage, a high degree of agreement between simulated and observed data has been obtained using expert knowledge. For some aspects of storm damage management, comparisons using annual statistics for the forest-based sector were made to validate the model. Feedbacks from previous storm crises in other regions also provided data specific to windthrow crises that could be used after verification. Unfortunately, no complete historical data were available in Belgium with which to validate entirely the model integrating storm damage by comparing its behaviour to real crisis dynamics. Nevertheless, the match between model results and real system behaviour after a storm was verified via expert knowledge.

4.2.7. Sensitivity Analysis

As mentioned, the model is not intended to give a precise stock value but to compare crisis management scenarios (in a "what-if" analysis). Due to the model's limited validation process, however, it was essential to determine the optimal level of precision needed when gathering data and assess model robustness through the relative influence of parameters varying over a certain range on the end result (Jiménez-Montealegre et al., 2002). To this end, sensitivity analyses were carried on in each module and on all parameters. A selection of studied parameters is presented in Table 3. For each selected parameter, the calibration value that gave the best fit between the simulated and real world was changed by ± 10 % increments while the other variables were left unchanged. Differences up to 15% between extreme values were considered significant (Jiménez-Montealegre et al., 2002). For converters with values that are functions of several variables, we first calculated the impact of a ± 10 % change on the initial value and then assessed how the error spread over the simulation period.

Sensitivity analysis results show that estimated stumpage prices have no influence on the system stocks but influence only the cash flow between owners and merchants and the total value of sales. Contrariwise, the devaluation rate applied to windfalls may have a significant impact on the amount of sales: the higher the devaluation, the faster the sales of windfalls, but the relation appears not to be linear. Changes in demand and offer do not influence the time required to sell windfalls but have huge impacts on the stock of unsold timber after 60 months. Thus, if decision-makers focus only on windfalls mobilization, those parameters are not crucial; when considering the impacts on forest owners, however, they should be determined carefully. In the harvesting module, the impacts of ± 10 % variation are less obvious. The impacts of changing mechanical harvesting capacity (*i.e.*, number of harvesters or productivity) on the total harvesting capacity may be explained by the greater contribution of mechanical harvesting relative to that of manual harvesting. On the other hand, errors in the estimation of manual harvesting capacity (*i.e.*, number of fellers or productivity) have a marginal impact on total harvesting capacity. In the transport module, changes of ± 10 % in the average distance between forest areas and storage terminals do not significantly affect the time needed to store windfalls. This result does not indicate that this distance is optimal (see below), but it does reveal that error in its estimation has no influence on the model. Conversely, variations in transport capacity (*i.e.*, number of trucks or productivity) influence the total amount of roundwood transported to industries.

Table 3. Effect on model indicator of increasing or decreasing the selected parameters by 10%. Results express the difference from the reference state. The sign (-) reveals an under-estimation. Figures in bold indicate a significant difference (over 15%) between extreme values

Parameter	Module	Indicator	−10%	+10%
price init	Purchase	Time to sell all windfalls	-	-
		Unsold timber after 60 months	-	-
wind dev	Purchase	Time to sell all windfalls	−20%	7.7%
		Unsold timber after 60 months	−14%	11.5%
demand	Purchase	Time to sell all windfalls	−4%	4%
		Unsold timber after 60 months	40%	−48%
offer	Purchase	Time to sell all windfalls	-	-
		Unsold timber after 60 months	−44%	44%
harvesters	Harvesting	Total harvesting capacity	−8%	8%
		Windfalls harvested	−8.7%	7.9%
		Total volume harvested	−7.7%	6.8%
mec prod	Harvesting	Total harvesting capacity	−8%	8%
workforce	Harvesting	Total harvesting capacity	−2%	2%
man prod	Harvesting	Total harvesting capacity	−2%	2%
dist store	Transport	Time to store	−4%	4%
tr fact	Transport	Round wood transported to industry	−7.8%	7.8%
nb trucks	Transport	Round wood transported to industry	−8%	7.8%
im hardw	Industry	Local hardwood processed	−1.2%	1.2%
ex hardw	Industry	Local hardwood processed	8%	-

Price init: stumpage prices before the storm; wind dev: devaluation of windfalls stumpage prices (first year); demand: demand for timber; offer: timber put on the market; harvesters: number of harvesters; mec prod: the mechanized harvest productivity; workforce: number of fellers; man prod: the manual harvest productivity; dist store: the mean distance of forests to storage terminals; tr fact: the truck productivity factor; nb trucks: total number of trucks available; im hardw: hardwood importation; ex hardw: hardwood exportation.

As mentioned, the sensitivity analysis results are also useful for evaluating which parameters are main influences on the stocks and fluxes of the system. For instance, if their influence were strong, decision-makers would know that those parameters might be key levers of the system when using the DSS based on the model (see section below). The exercise was made for the average distance between forest areas and the storage terminals parameter (dist store). Starting from a reference of 30 km, the sensitivity analysis showed no significant impact of a 10% decrease or increase (see Table 3). However, when larger or smaller distances were taken into account (*i.e.*, 10, 20, 40, 50 km), the time required to store the targeted amount of windfalls varied between -17 % (10 km) and +20% (50 km). The mean distance between storage places and forest areas thus appears to be a key element of wood storage policy after a storm. Such thorough analysis should be used to improve forest-wood chain functioning before the next storm, with the limitation that the state of the system is constituted by the dynamic combination of 61 converters and 18 flows; thus, merely optimizing each individual parameter will not lead to the perfect scenario for all stakeholders.

4.3. MODEL APPLICATION: THE WIND-STORM DECISION SUPPORT SYSTEM

4.3.1. The Decision Support System

A DSS named "WIND-STORM" (Wind Damage Strategic Tool for Risk Management) was developed on the basis of the WALFORM model in order to provide a multitasking tool for supporting strategic decision-making. WIND-STORM was built to support three kinds of objectives: (1) to compare crisis management scenarios in the aftermath of storms in order to select the best management scenario for the whole forest-based sector; (2) to identify the main bottlenecks in the wood mobilization chain for the chosen scenario in order to solve them; and (3) to run prospective analyses on the system outside crisis periods to apply structural solutions to specific issues. The first two uses of the DSS rely on real data and market conditions corresponding to the month in which the windstorm strikes, while prospective analyses are based on estimated parameter values derived from the normal functioning of the regional forest-based sector. The software is linked to an online storm damage assessment application that supplies input data for simulations (Riguelle et al., 2009). In addition, an associated graphical module (Excel spreadsheets) allows visual representation and a comparison among simulations.

4.3.2. Case Study

Value added of this DSS for storm crisis management is assessed below through a comparison between four crisis management scenarios (SC1 to SC4) and a business-as-usual (BAU) situation (in which authorities take no action after the storm). For a hypothetical storm occurring in January 2015, scenarios based on an overall estimated damage of 8×10^6 m^3, an average 40 % decrease in windfall stumpage prices and a 10 % reduction in the demand for local resources were run. The damage is split as follows: 70 % for spruce and 10 % for the other 3 groups of species. A 25 % reduction in harvesting productivity in damaged areas is applied.

Table 4 presents a selection of the parameters that were alternatively changed in the crisis scenarios to evaluate their effect. It is important to note that this selection is only one case study among a wide range of possibilities. In a real crisis context, technical and financial constraints will reduce the initial array of scenarios. In the BAU scenario, all parameters were set at their initial (calibration) values, except for those specifically related to windfalls purchasing, harvesting, and transport capacities, which were set to 50 %. For each crisis scenario, we investigated the effects of several policies or supporting measures on post-storm operations, assuming that the selected parameters were among the most relevant for storm damage management. For the purchase module, several values for exchange rate (see parameter P1 in

Table 4), purchase capacity dedicated to windfalls (P2) and offer shift (P3), as well as the activation of payment delays (P4) are evaluated. For harvesting operations, the number of fellers (H5) and harvesters (H6) available for work are modulated in the crisis scenario. The variation in harvesting capacity dedicated to windfalls (H7) and the application of delays in harvesting pre-sold timber (H8) are also tested. For the transport module, the study focuses on the number of trucks (T9), the maximum authorized weight of the trucks (T10), and the shift in transport capacity dedicated to windfalls (T11). The impact of wood storage is tested through the stored amount and the minimum storage period (T12 and T13). Finally, for the industry module, a 10% drop in softwood and hardwood imports (I15 and I16) and a restriction on hardwood species export (I17) are simulated.

Table 4. Selected parameters for business-as-usual (BAU) and crisis scenarios (SC1 to SC4)

Parameters	BAU	SC1	SC2	SC3	SC4
P 1. Exchange rate (%)	0	0	10	10	20
P 2. Purchase capacity dedicated to windfalls (%)	50	50	66	66	66
P 3. Offer shift	-	-	a	b	c
P 4. Payment delays (years and %)	-	1, 50 %	-	1, 50 %	-
H 5. Number of fellers (workforce)	105	125	136	136	136
H 6. Number of harvesters	105	125	136	136	136
H 7. Harvesting capacity dedicated to windfalls (%)	50	66	66	75	85
H 8. Harvesting delays (months)	-	-	-	18	-
T 9. Trucks	150	150	150	150	175
T 10. Maximal weight (T)	44	44	55	55	55
T 11. Transport capacity dedicated to windfalls (%)	50	66	66	66	75
T 12. Storage (Mm^3)	-	-	-	1,2	1,6
T 13. Minimum storage time (months)	-	-	-	12	24
T 14. Truck repartition (% for storage)	0	0	0	40	40
I 15. Importations shift hardwood (Mm^3/year)	-	−10 %	-	-	-
I 16. Importations shift softwood (Mm^3/year)	-	−10 %	-	-	-
I 17. Priority to export SW (Yes/No)	Yes	No	Yes	Yes	Yes

4.3.3. Results

Charts in the embedded graphical module cover a broad range of indicators for the four subsystems and provide a comparative perspective for decision-making. The WIND-STORM software can also provide more detailed information for decision-makers, such as economic losses for owners, storage costs, or commercial trade balance (exports minus imports). This section presents a brief overview of the potential outputs of the DSS for the five selected scenarios and their interpretation in terms of crisis management. The considerations below are valid only for this specific case study. Results will be discussed for each module first and then from a systemic point of view.

Figure 20A shows that, without specific measures, about 28 months are needed to sell the entire amount of windfalls in the BAU scenario. An increase in the purchase capacity dedicated to windfalls from 50 % to 66 % can reduce this length by around 8 months. The length of the sale period is not really affected by payment delays (SC1 and SC3), but this measure helps to sell more windfalls in the first year following the storm. Figure 20B illustrates that the excess supply reaches over 6×10^6 m^3 without any action (BAU scenario) and tends to balance at around 5×10^6 m^3 for SC1 and SC2, more than an average annual harvest (4×10^6 m^3). Only a huge reduction in supply, by half the usual amount over the simulation period, leads to a balanced system (SC4) after 60 months.

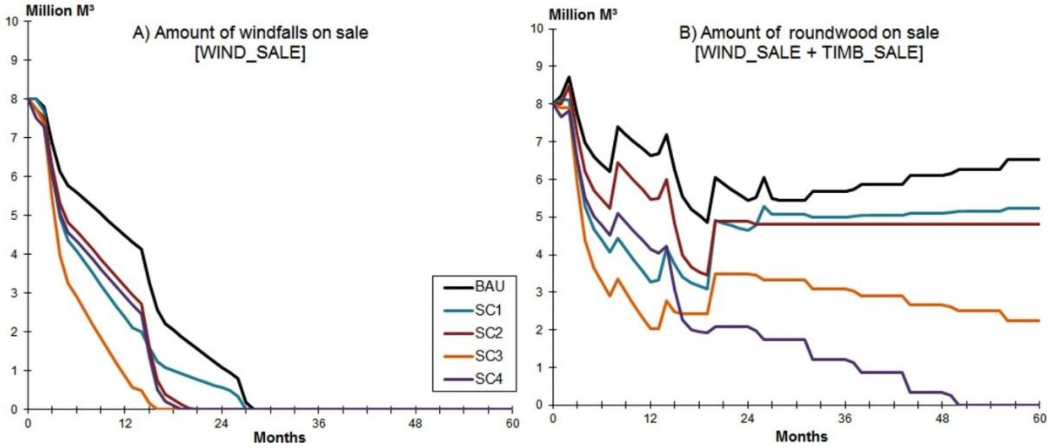

Figure 20. Stocks to sale (million m3) for business-as-usual (BAU) and crisis scenarios (SC1-SC4)

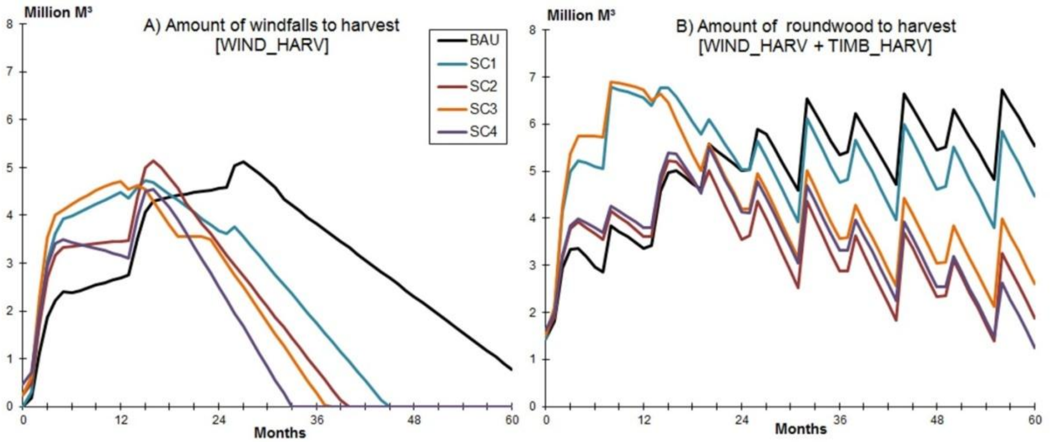

Figure 21. Stocks to harvest (million m3) for business-as-usual (BAU) and crisis scenarios (SC1-SC4)

Figure 21A displays the results of the simulations for the harvesting subsystem. Predictably, strengthening harvesting capacity had a clear impact on the harvesting time. If no measure is taken, harvesting the amount of windfalls in 60 months is clearly impossible; with a 20 % increase in capacity, however, the harvest time will be reduced to 45 months. Even with an increase in harvesting capacity (*i.e.*, by investing in the acquisition of mechanical equipment), operations will last roughly three years for windfalls (SC2, SC3 and SC4). Figure 21B shows that the total roundwood stock to harvest declines to its initial level after only five years in the SC2 and SC4 scenarios.

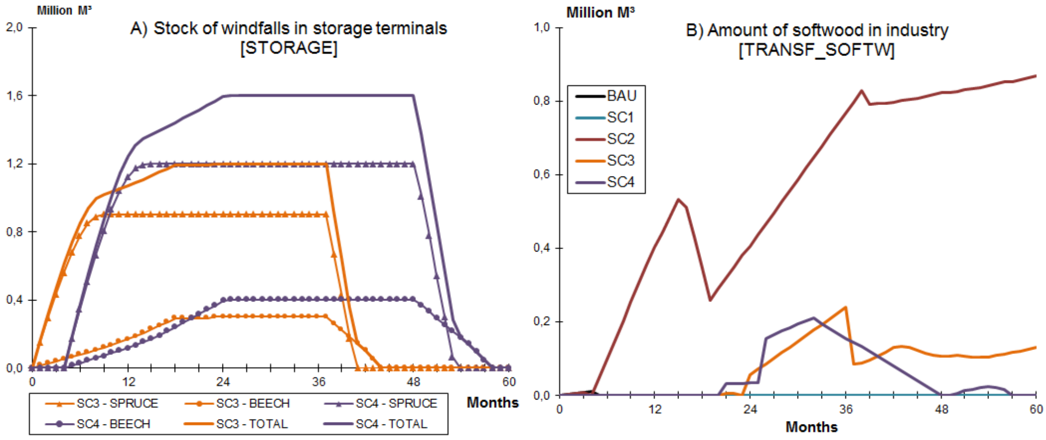

Figure 22. Stocks (million m3) for business-as-usual (BAU) and crisis scenarios (SC1 to SC4)

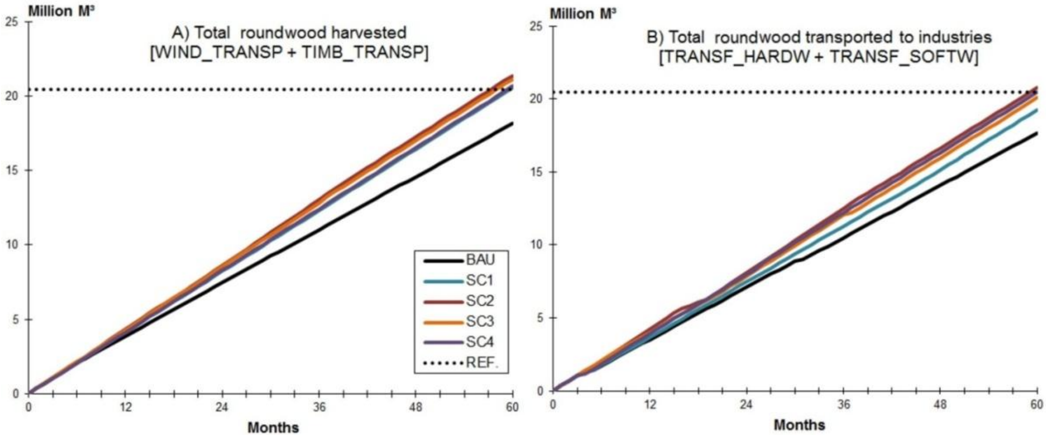

Figure 23. Roundwood (windfalls plus timber) cumulative flows (million m3) for business-as-usual (BAU) and crisis scenarios (SC1 to SC4)

Figure 22 illustrates how transport and storage crisis policies influence system behaviour. The quantities of stored roundwood (exclusively windfalls) correspond to the assigned objective of 1.2 and 1.6 × 10^6 m^3 (see Figure 22A). For SC3, 18 months are needed to reach the targeted value of the stock, while 24 months are necessary in SC4. In both cases, the volume of beech available each month is the limiting factor in filling all storage terminals. As transport capacity is optimized at that time, the removal from storage will last less time. The DSS estimates the costs of storage for water sprinkling at €24 and €35 million, respectively, for an average cost per stored cubic meter of €20 in SC3 and €22 in SC4. The need for storage policy is made quite clear when looking at the surplus stocks in industry for softwood species (see Figure 22B). Concerning softwood, wood storage contributes to reducing (SC3) or eliminating (SC4) excess deliveries relative to SC2 (at the same transport rate).

From a systemic point of view, all scenarios lead to a surplus of sales relative to the five-year reference value of forest sector needs. In these simulations, a 10 % demand reduction does not balance a sharp decrease in stumpage prices. The first bottleneck in the wood mobilization chain appears to be the harvesting capacity (see Figure 23A). Without any strategic measure (BAU), the loss of harvesting productivity in damaged areas leads to a loss of 5 × 10^6 m^3 at the end of the simulation period relative to the reference value. However, this objective is met when harvesters and the workforce increase by 20 % (SC1 to SC4). The second bottleneck appears to be the transport of windfalls and timber products (see Figure 23B). An increase in the maximum authorized truck weight from 44 to 55 tons is enough to bring the necessary supply to industry (SC2). However, when the storage option is activated (SC3 and SC4) the transport capacity must be boosted. Transport capacity can also be improved by increasing the number of trucks. Finally, the overall industry demand for local resources (the dashed lines in Figure 23) is supplied only in SC1 and SC2, for which there are no storage operations.

4.4. DISCUSSION

Decision makers in storm crisis management often lack the tools for evaluating the consequences of their strategic decisions. Crisis measures that appeared efficient when considered in isolation have actually been counterproductive because the forest-based sector was not considered from a systemic point of view, indicating the need to develop a new type of DSS able to reproduce the dynamics of forest operations (e.g., sales, harvesting, transport, transformation) in a disrupted market situation. The WALFORM model developed and calibrated for the Wallonia region in Belgium serves as the basis of this DSS. Based on the system dynamics modelling approach, the WIND-STORM tool focuses on system behaviour rather than numerical results (Buongiorno, 1996). The DSS, based on 61 parameters, can simulate a wide range of crisis management scenarios. A graphic user interface and advanced database management capabilities for data access, key requirements for an efficient DSS (Muys et al., 2010), have been developed.

The results of the case study presented in section 5.3.3 suggest that the DSS reflects the variations among scenarios quite accurately. More generally, the DSS provides a wide spectrum of information to the end-user, allowing all types of scenario to be simulated. WIND-STORM can also be used prospectively. Simulations should be run between two crises to identify which key elements to focus on when the next calamity occurs and find structural solutions for the system bottlenecks. The DSS could be optimized by automating the simulation phase to generate a portfolio of scenarios derived from the initial level of damage and then selecting those that correspond to the decision-makers' options. However, a fully optimized process is not possible because qualitative criteria such as political, social, environmental, and ethical considerations are also part of the decision process. Though the DSS offers decision-makers a wide range of possibilities, it cannot provide the optimal scenario for storm damage management.

This paper does not pretend to identify new storm damage management options, but it can foster systemic approaches in decision-making. In this field, this study's proposed use of system thinking and methodology supported by a modelling tool is novel. Reports and analyses on storm events management (Mortier and Bartet, 2004, Raetz, 2004, Barthod, 2009, Bavard et al., 2013) have often mentioned a lack of coordination between forest-based stakeholders and decision-makers. The joint use of a DSS in a crisis unit forces decision-makers and forest stakeholders to share opinions and to compromise, thus fostering successful crisis management.

Nevertheless, this approach has some weaknesses. The first concerns the model development and the necessity of representing the real forest-wood chain with a limited number of parameters. This need introduces minor compromises for convenience (Vanclay, 2014) and generates unexpected effects. However, sensitivity analyses conducted on selected parameters tend to confirm the robustness of the model outputs (Kallio, 2010). Nevertheless, model sensitivity should be further investigated to inform end-users of the expected impacts of all parameters on the system. A second drawback is the complexity of the model and the difficulty users may have understanding the mechanisms behind the results (Wibe, 2005). Decision-makers may not feel confident when using a DSS as a "black box" to produce policy recommendations (Reynolds et al., 2008), as they must explain why and how their decisions are made. According to (Buongiorno, 1996), a good model is ultimately the one that is used. In other words, if decision-makers cannot follow the reasoning used by the system, they are not likely to understand its output or follow the DSS' recommendations (Garcia-Gonzalo et al., 2013). To address this issue, stakeholders were involved in the modelling step (Voinov and Bousquet, 2010), and training was provided to end-users afterwards. Finally, data availability and updates may be another limitation. The use of the DSS must be prepared before a crisis occurs, and the data must be continuously updated by the forest public service, the recipient of the DSS after its development. This need may interfere with the correct use of the tool during emergencies.

Despite these limitations, the DSS could be highly valuable for the forest-based sector if, and only if, the decisional context is appropriate. The search for a well-balanced solution relies on data coming from stakeholders, and false or truncated information will lead to poor decisions. More generally, sound decisions require honesty and confidence among all stakeholders, including public authorities, the forest community (e.g., scientists, practitioners), and actors in the forest-wood chain. Public authorities must keep the global welfare of the forest sector in mind because strategic decisions will be cost-efficient only if they are balanced and satisfactory for all parties. Meanwhile, the role of scientific community is to inspire confidence in the approach—as system thinking is seldom used in forestry—and address methodological concerns. In addition, while computer systems can deal with the structured portion of a problem (Hujala et al., 2013), the judgment of the decision-maker is required to deal with the unstructured part (Shim et al., 2002). Thus, decision-makers must seek advice from the forest community throughout the decision-making process. This kind of participatory process is also useful for the forest sector as a whole because sound strategies enhance the efficiency of the use of public resources (Tuomasjukka et al., 2013).

Of course, this DSS is just one tool among several that could help public authorities, decision-makers, and operational managers in the aftermath of huge storms. Other critical aspects of storm damage management should be addressed in future works—damage assessment and timber storage, for instance. Damage assessment is very important because the post-storm strategy is based on it. Appropriate methods of collecting data quickly after the calamity are thus needed, as well as IT tools for facilitating data transmission and processing. A tool for supporting the tactical management of storage operations is also very important, as this paper showed that the location of storage terminals and associated transport capacity are key elements of storage policy. Using a Geographical Information System (GIS) to identify potential storage locations before the storm and ideal localizations of terminals after the event could also be very useful. From a regional point of view, Wallonia still lacks the risk assessment tools for predicting the probability of damage in forest areas and producing risk maps with which to inform decision-makers of risk levels. The risk assessment approaches used in bordering countries (Gardiner et al., 2008, Hanewinkel et al., 2011) should be tested and adapted to regional specifications in order to provide a fully integrated approach to wind-risk management and facilitate the transition from risk assessment to crisis management.

5 CONTINGENCY PLANNING

Contingency plans are usually established by public authorities or private companies to mitigate impacts of sudden disasters on civilians and/or business. Applied to forestry and storm damage management, contingency planning is a key element for improving preparedness and response to windthrow crises. After some general considerations about the concept and its implementation, the section presents the Windthrow Contingency Plan (WCP), a major output of this thesis that have been devised with and for public authorities in Wallonia, Belgium.

5.1. CONCEPT

A contingency plan is a plan devised to manage the unusual outcomes of a business. Companies usually develop contingency plans for preparing themselves for bad outcomes that could result in inefficiency and financial losses. Public authorities or NGOs can also devise contingency plans in order to, for instance, be prepared for assisting the population and providing assistance in case of emergency. In every case, a contingency plan can be view as a “Plan B” as it is an alternative to a business-as-usual management.

According to that, contingency planning is a key aspect of risk management, disaster recovery and business continuity. More particularly, in risk management, a contingency plan is expected when a residual risk, though unlikely, remains too important for risk managers as it could have catastrophic consequences. Indeed, the purpose of contingency plans is not to lower the risk anymore, but to mitigate hazards’ impacts through appropriated measures. Nevertheless, some pitfalls have to be kept in mind before starting the planning process. First, people are often poorly motivated to invest in the development of a “Plan B” because they are strongly invested in the “Plan A”. Contingency planning is then view as a lack of time and money. In addition, contingency planning is not often considered as an urgent activity especially if crisis occurrence probability is low. Contingency planning therefore requests a strong commitment from the decision-holders to succeed.

5.2. PROCESS

The writing of contingency plans requests exploring and preparing for emergency cases that can put an organization into troubles. In this context, risk assessment processes help to figure out and prioritize the risks that could occur. Before starting to write a contingency plan, stakeholders should answer the three underlying questions of contingency planning:

- What could happen?
- What shall we do in response?
- What should we do in advance to prepare?

Contingency planning is not a "one-size-fits-all" process. Indeed, there is no guarantee that a generic contingency plan will handle all specific issues. However, when separated plans are devised for specific risks, common features (guidelines) must be respected to enhance their appropriation by end-users. From a formal perspective, it is also important to keep the plan simple and to adapt language and content to the future audience that will have to implement the plan.

5.3. APPLICATION TO STORM DAMAGE MANAGEMENT

5.3.1. Contingency plans

In the particular context of windthrow management, contingency plans are effective tools for public authorities and the forest-based sector for handling and controlling the consequences of destructive storms. As huge storms are rare events, experienced people and knowledge are likely to disappear progressively between two crises (Hartebrodt, 2014) and the idea that the internal expertise will be sufficient to deal with storm's impacts often leads to unpreparedness. Past events reveal a tendency to act too fast after natural disturbances in forests, following the idea of "back to normality" (Hartebrodt, 2014). However, rushing is not recommended and contingency planning will help to ensure a better implication of people involved in the process. Without clear definition of strategic priorities, conflicting operative processes will also arise. In this context, contingency planning can help by defining core objectives, providing methodology and supporting decision.

Box 1. Belgian legislation regarding contingency planning

In Belgium, the Federal Law of 15 May 2007 regarding Civil Security defines the legislative framework and obligations that bind stakeholders concerned by civil security management and contingency planning. On the one hand, public authorities have planning and response commitments, whereas their involvement varies upon the emergency level and the geographical scale. On the other hand, civil services, either public or private, must also follow the Civil Security Law for preparing and responding to emergencies that would threaten the population. According to the Law, three types of contingency plans (CP) can be elaborated:

- **Multidisciplinary Contingency and Response Plans** contain general guidelines needed to manage emergencies at a predefined level of intervention. It can be completed by specific additional guidance for specific risks.
- **Response Plans** set particular rules of intervention for every stakeholder involved in civil security management (i.e. Medical Response Plan).
- **Internal Contingency Plans** are documents adopted at the company or institution level, aiming to limit adverse impacts of an emergency, through organisational or operational measures.

Private companies are not bind to devise contingency plans, except if they arise from sectoral European, national or regional legislations (i.e. nuclear safety, SEVESO Directive).

A good illustration is the contingency plan developed in France for the state forest service (ONF) in the following of 1999's Lothar and Martin gales (Bartet and Mortier, 2002). The authors considered that "business-as-usual" procedures were not efficient enough for managing crisis (Mortier and Bartet, 2004). They pointed out that inappropriate measures taken by unprepared organisations worsen the initial situation. Referring to Lagadec (1991), some frequent pitfalls of are very insightful: hyperactivity, risk avoidance strategies, lack of communication, confusion in roles and responsibilities, high pressure put on experts and archaic management. They pleaded for a flexible crisis support, paving the way for an effective crisis management context (Mortier and Bartet, 2004). Regional contingency plans were also elaborated by the forest sector in France in the last decade (FIBOIS, 2010a).

In Germany, damaging events due to extreme weather are considered as a central threat for the forestry sector. It led to the publication of the Forest Crisis Management Advisory Guide (Kaulfuß and Hartebrodt, 2010, Chtioui et al., 2015) which deal with those issues through an integrated approach. Their statement is that a wide range of damages can be avoided or minimized through prevention and good preparation (Chtioui et al., 2015). The Guide provides several manuals for dealing with specific topic with a special emphasis put on prevention and preparation measures. Among those manuals, Odenthal-Kahabka (2005) coordinated the "Storm Handbook" for coping with storm damaged timber. While this handbook deals primarily with technical instructions (see below), it also contains strategic considerations that can be for devising contingency plans.

Another example comes from Scotland, where the Forestry Commission has developed a strategy for dealing with windblow events in Scottish forests (Forestry Commission Scotland, 2014). The Scottish Windblow Contingency Plan (SWCP) first introduces the background and the definition of a windblow event as well as the key contact available during a critical event. The plan follows the five core principles of Integrated Emergency Management (IEM): assessment, prevention, preparation, response, and recovery. A major feature is that the SWCP based on Regional and Local Resilience Partnerships. Resilience Partnerships encompass organisations designated as emergency responders in the Law (local authorities, emergency services) and therefore coordinate risk management at the local level. This is interesting from our point of view for combining local issues and specificities with national windblow management rules and for enhancing people's involvement in the risk management process.

The SWCP provides that when wind gusts are expected to exceed 80 mph (128 km/h) stakeholders must be alerted by email. When gust of wind up to 90 mph (144 km/h) are forecast, the crisis advisor will act the launching of the Plan. In addition, the forest industry should initiate precautionary measures, which include moving essential equipment, placing on standby individuals, and warning the public and forest event organisers. After a potentially damaging storm event, the Scottish Plan two kinds of responses: a multidisciplinary emergency response led by Resilience Partnerships and a sectoral response by the Forest industry under the lead of the Strategic Windblow Action Committee (SWAC). It also gives clues for developing a harvesting, marketing and restocking strategy and for monitoring and evaluating the plan implementation during and after the crisis.

Contingency planning was also put at the top of the agenda in Switzerland after the storm Lothar. The Swiss Federal Office for the Environment (FOEN) developed a guide for coping with storm damage management (OFEV, 2008) that contains strategic and technical information. From the strategic perspective, the guide provides the basis for implementing an integrated risk management approach through its three pillars: prevention, response and recovery. The plan also reminds the six strategic goals that have to follow when coping with windthrow: (i) allow sound and rapid damage management (ii) ensure a high level of security in forests ; (iii) maintain the protective function of forests ; (iv) maintain and/or improve biodiversity (v) limit timber market disruption (vi) prevent soil fertility losses.

5.3.2. Technical handbooks

Technical handbooks are not considered as contingency plans sensu stricto because they do not deal with all aspects of crisis management. However, those guides are set out for informing operational decisions after huge storms, and thus can be considered as a support for decision-making. They can also be embedded in a contingency plan (OFEV, 2008, FIBOIS, 2010b, Riguelle, 2010).

Based on the wide knowledge about storm damage management, technical handbooks usually encompass lot of best practices and provide simple decisional tools. These documents relate to several aspects of windthrow management like damage assessment, timber removing, harvesting and storage operations, marketing of wood products or forest restoration. An overview of sound windthrow-related technical handbooks is given in the Table 5.

Table 5. List of some Technical Handbooks related to windthrow management

References	Scope	Topics
FAO/ECE/ILO (1996)	World	Damage assessment Harvesting operations Marketing Forest restoration
FIBOIS (2010b)	France (Alsace Region)	Damage assessment Harvesting operations Transport Timber storage
Odenthal-Kahabka (2005)	Germany	Damage assessment Harvesting operations Marketing Forest restoration
OFEV (2008)	Switzerland	Damage assessment Harvesting operations Marketing Forest restoration
Oosterbaan et al. (2009)	The Netherlands	Damage removals
Pischedda (2004)	Europe	Harvesting operations Timber storage
Riguelle (2010), Riguelle et al. (2015b)	Belgium	Timber storage

5.4. THE WALLOON WINDTHROW CONTINGENCY PLAN (WCP)

5.4.1. Legal nature and origin

The Walloon Windthrow Contingency Plan (Riguelle, 2010, Riguelle et al., 2011) – mentioned below as the WCP – is an internal contingency plan adopted by the Directorate General Agriculture, Natural Resources and Environment (DGARNE) of the Public Service of Wallonia (SPW) in Belgium. The legislative and administrative contexts under which the WCP was developed in 2010 are quite complex (see Figure 24).

According to the national legislation (see Box 1 above), regional public bodies have no legal obligation concerning contingency planning. Nevertheless, they should collaborate with civil services because they play an active role in civil security operations as a logistical actor. For specific topics that fall under European legislations (e.g. the Floods Directive 2007/60/EC), the regional public bodies have sometimes to develop contingency plans to match with EU legal or funding requirements, but it is not the case for forestry yet. The reader should note that the absence of a common European forest policy does not concur to enhance a common storm damage management. Finally, the regional government can also define the framework for risk and crisis management. In 2016, as no binding legislation about natural risk management exists in Wallonia, one should rather talk about regional orientations that generate very generic guidelines.

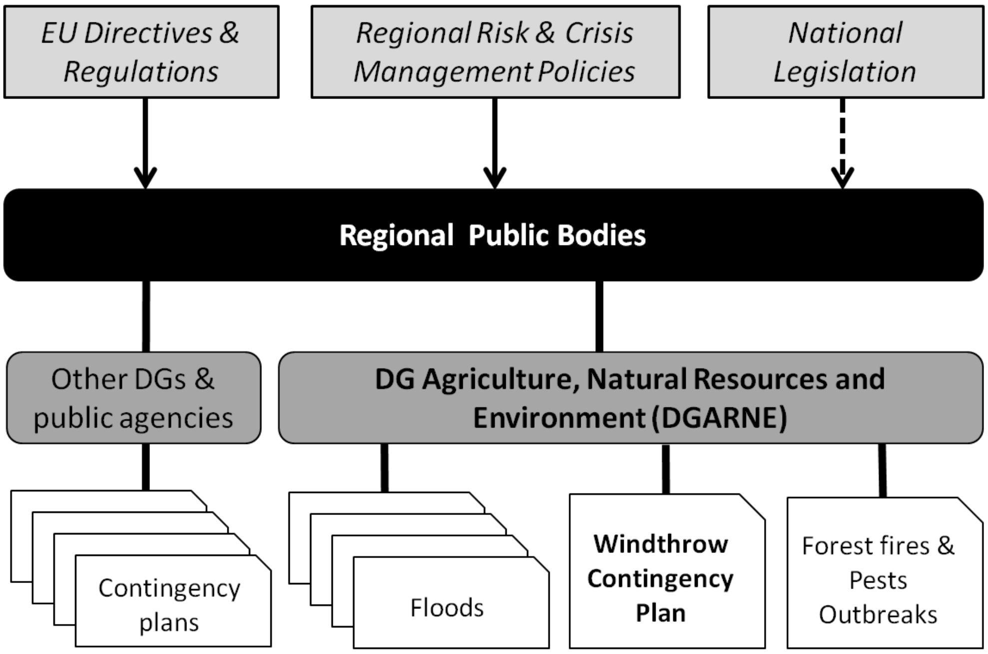

Figure 24. Contingency planning context in Wallonia, Belgium.

In this context, the WCP results mostly from a strategic commitment from the DGARNE to manage crises whose scope is under its administrative responsibility. The two main drivers for it are to mitigate economic impacts of natural or industrial disasters on the regional economy and to offer a reliable support to the population. Furthermore, contingency planning is part of the quality management system of the institution. The Walloon Contingency Plan was the first thematic plan developed in this context within the Directorate General, paving the way for other contingency plans relating to topics such as forest fires, pests outbreaks, floods, droughts, pollution (water, soil and atmosphere) or industrial accidents.

5.4.2. Structure and content

The Plan has been built mainly on the structure defined previously for the French State Forest Administration (ONF) by Bartet and Mortier (2002). The WCP is a plan dedicated to the Department of Nature and Forests (DNF), the regional forest service, and therefore does not involve directly other public agencies. However, its prerequisite is to deal first with civil emergencies that could happen in the forest areas and their surroundings, and to handle forest-related issues in a second step. Thus, the forest service will act in support of civil services during the first days. The WCP is divided into five phases, which also encompass the five core principles of Integrated Emergency Management (Figure 25):

- PHASE 1 ➔ General organisation and preparation to crisis management
- PHASE 2 ➔ Early warning procedures and preventive measures
- PHASE 3 ➔ Emergency measures
- PHASE 4 ➔ Damage assessment and short-term measures
- PHASE 5 ➔ Long-term management and crisis recovery

The WCP includes a general procedure (GP) that frames the whole storm crisis management process and refers to more detailed specific instructions (IC). The general procedure has to be read by all stakeholders outside crisis periods, in order to avoid unpreparedness. This general procedure is a generic framework, but it does not intend to be rigid. Indeed, crisis managers still have the possibility to adapt to unexpected outcomes. There could be alternatives, provided they are discussed within the crisis unit. In addition to general procedure and instructions, some thematic handbooks provide technical information to the decision-makers.

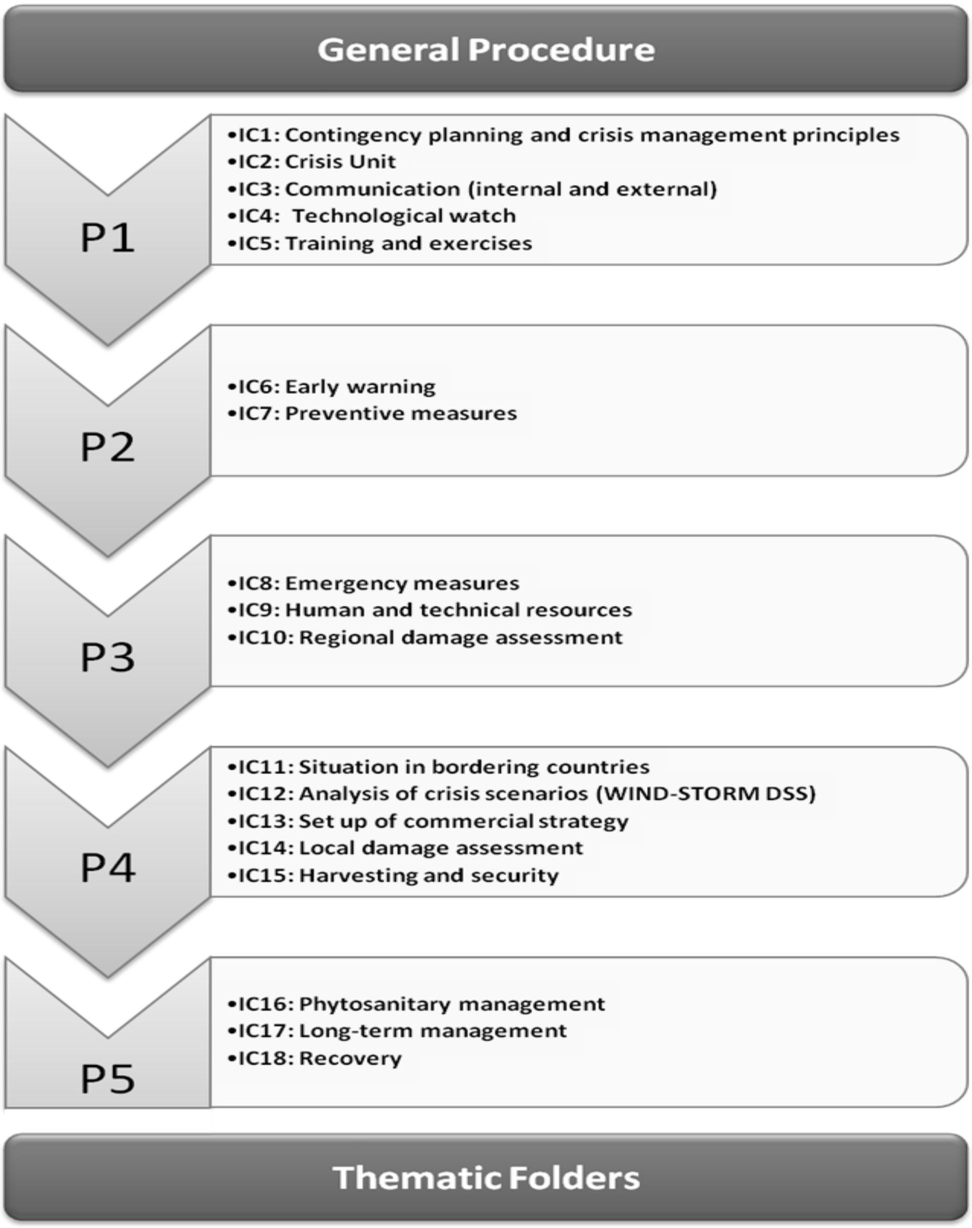

Figure 25. Structure and content of the Walloon Contingency Plan. For each successive management phases (P), specific instructions (IC) provide operational details

5.4.3. Main features

i. Coordination

At the regional level, two coordinating structures are identified in the Plan. The first is a permanent one, the Regional Crisis Centre (CRC), which coordinate crisis response for all public bodies in Wallonia. In addition, a Technical Crisis Unit (TCU) is established to manage windthrow-related topics during the crisis period. The TCU brings together the regional forest service (DNF), representatives from the private forest sector, timber merchants, harvesting and transport companies, members from sawmilling, pulp, paper and panel industries, and experts from scientific and academic institutions. The Technical Crisis Unit is the single central point of contact (SPOC) for all forest-related issues that arise after the storm. Their members define the regional strategy that should be followed by the forest-based sector. However, they should take decisions by consensus in order to enhance their applications by the forest-based sector. This is probably one of the major requirements for reaching an efficient post-storm crisis response.

ii. Communication

Communication is a key element within the storm damage management process, although it is often underestimated by the forest-based actors. The Plan makes a distinction between external and internal communication. The external communication, which encompasses relations with other levels of governance, media and the population, is managed by the CRC on behalf of the Crisis Unit. The internal communication follows the hierarchical route within the public administration, according to pre-established procedures. It main purpose is to circulate decisions taken by the TCU from the head of administration to decentralized forest management units.

iii. Technological watch

The operability of the contingency plan relies on a regular technological watch. This duty includes all the tasks that have to be done outside crisis periods to ensure a quick and reliable implementation of the WCP. It implies, among others:

integrating most recent scientific and technical knowledge, improving and correcting documents, writing new instructions and updating data requested by WIND-STORM software (see chapter 5). The technological watch is, of course, part of the continuous improvement approach that must be implemented within the regional forest service.

iv. Early warning

In Belgium, meteorological alerts are displayed by the Royal Meteorological Institute (RMI). The RMI also relays information from Meteoalarm, a service provided by EUMETNET, the Network of European Meteorological Services. Whereas high wind speeds can be forecasted within a few days at the national level, the synoptic evolution of huge storms, their real trajectories and the associated maximal gust speeds are quite impossible to predict. That is the reason why, according to the WCP, preventive measures (see v) must be activated as soon as the expected average wind speed reaches the level 11 on the Beaufort scale. The warning must be displayed through the public administration in order to activate these preventive measures. As the CRC gets an hourly report on the observed wind speeds by the RMI, it will be able to decide either to maintain or to cancel the preventive measures.

v. Preventive measures

The preventive measures are threefold:

- Circulation in forest areas must be forbidden during the warning period. This measure relies on a legal basis that allows decentralized forest management units to close road access to forest areas for a 7-days period, at least. It implies to display specific signage at each (main) forest access.
- Alerting and/or requisitioning staff members in order to be able to react quickly after the storm.
- Displaying a warning message to the population through various communication supports (TV, radio, web, and social media).

vi. Emergency measures

Just after the storm, four actions are prescribed, in order to assess the crisis level and deal with civil emergencies:

- Internal feedback: the Head of administration must have a contact with decentralized units to deliver emergency orders. Reversely, decentralized units must provide bottom-up feedback for assessing field situation.
- Supporting civil services: the regional forest service is expected to put some of their human and technical resources at the disposal of civil services, for supporting operations in or near forest areas. They could also bring expertise and advices during the logistical process.
- Re-establishing forest accessibility: a priority is to guarantee free access to main forest roads to allow emergency operations in a first time, and to allow damage assessment in a second time.
- Activating the Technical Crisis Unit: the TCU is convened within a few days in order to assess the post-storm situation in forests and take first crisis measures if necessary.

Box 2. Storm damage assessment in Wallonia (Belgium)

In Wallonia, storm damage assessment methodologies have been developed to inform decision-making after huge storms. Those methodologies encompass both regional and local damage assessment, but mainly focus on the regional evaluation of storm impact. Indeed, a quick and reliable estimation of damage is a crucial input for the Technical Crisis Unit in the aftermath of storms in order to assess the crisis magnitude and activate appropriated crisis measures. It also allows them to run prospective simulations and compare several crisis management scenarios with the support of the WIND-STORM DSS (see chapter 6).

➔ More details about these methodologies can be found in chapters 6 and 7 and in Riguelle et al. (2008).

vii. International assessment

Due to the geographical location and extent of Wallonia, a thorough screening of storm damage is a prerequisite to the settlement of any regional strategy. This screening must be lead in both Belgium' neighbouring countries (France, Luxembourg, The Netherlands, and Germany) and other European countries (Switzerland, Austria, Sweden, Finland, UK, etc.) because, for instance, commercial agreements can be threatened by windthrow crises in other countries. However, those contacts are also an opportunity to enhance cooperation with affected countries, as we consider that a collaborative approach will be more profitable than individual efforts.

viii. Strategic decision-making

During this decisional step, the TCU defines the common strategy to be followed to mitigate storm impacts at each step of the forest-wood chain. Decisions are supported by decision-support systems and expert knowledge. Among others, the TCU defines the regional strategy for selling, harvesting, transporting, storing and exporting windthrows. However, tactical and operational aspects are not directly handled by the crisis unit.

ix. Phytosanitary management

Pests' outbreaks arising in the first or second year after huge storms are major threats for forests (Bouget and Duelli, 2004, Jönsson et al., 2012, Stadelmann et al., 2013). As noted before, secondary damage resulting from bark beetles, for instance, are strongly correlated to the initial amount of windthrow (Mezei et al., 2014). This issue highlights that windthrows cannot be manage solely, but must be integrated in a wider risk management approach. Specific contingency plan dedicated to phytosanitary management in Wallonia should thus be developed in accordance to the WCP. Without any specific contingency plan for phytosanitary management, guidelines to manage the secondary risk of damage are provided by the WCP, with the aim to raise awareness of decision-makers about this topic.

x. Long-term crisis management and recovery

The long-term management of windthrow implies a permanent monitoring of forest operations and timber stocks. These indicators are useful for comparing real situation with the optimal scenario defined in the beginning of the crisis and reallocating resources according to this analysis. Among priorities at this stage, timber storage management (see chapters 6 and 7) is a key element to foster crisis recovery. Long-term windthrow management is not yet considered as an acute crisis management process in the contingency plan whereas storm negative impacts on the forest resources and the forest-based sector can least for many years. Nevertheless, when the overall situation is under control, the TCU must officially announce to all stakeholders the end of the crisis. From that moment, a revision of the WCT should take place more actively under the supervision of the DGARNE (see section 5.4.5).

5.4.4. Plan testing, training and exercises

Plan testing, training and exercising are crucial activities for improving plan effectiveness and stakeholders' preparedness. In this context, one should distinguish between testing operations that aim to validate the effectiveness of mitigation measures, trainings that contribute to enhance stakeholders' reactivity towards plan activation and exercising that helps to identify planning weaknesses. The General Procedure of the WCP clearly highlights the need for trainings and exercises. Once a year, a specific feature of the WCP should be tested. A specific instruction provides some additional guidelines to decision-makers for planning those activities; however, it does not intend to give them predetermined scenarios.

5.4.5. Continuous improvement

Every contingency plan should be a living document regularly updated to remain current with systemic and organizational changes. This is also the case for the WCP, which need to be in line with fluctuating political orientations, moving administrative procedures, and changing market condition. Otherwise, the WCP would probably be ineffective for crisis management.

Box 3. IT-support to storm damage assessment in Wallonia (Belgium)

The conception of an Intranet application to support the realisation of the regional storm damage assessment procedure is another practical output of this thesis. Through this application, the end-users – either forest services' staff or crisis unit – can access to on-line information and services that ease the production and interpretation of damage assessment results. More particularly, the application includes functionalities such as:

- For Forest Services' staff:
  - Downloading of maps and documents needed for field inventories
  - Filling of electronic forms for damage reporting
  - Consultation of damage assessment results for their management units

- For the Crisis Unit:
  - Following of the damage assessment progress (sampling units visited)
  - Consultation of damage assessment results for the whole Region
  - Identification of more heavily damaged areas.

- For the Application caretaker:
  - Uploading of maps and documents needed for field inventories
  - Update and backups of IPRFW database
  - Delivery of access logins and determination of clearance level
  - Launching of new windthrow events and assessment procedures

Advantages provided by such on-line interface are manifold. First, it enables direct filling of the results by decentralized forest services, with no source of failures as, for instance, the loss of data sheets and transcription mistakes. Furthermore, it provides them up-to-date information and helpdesk support. Finally, the program does not require calculation by the crisis unit because it gives immediate assessment results, by area and by type of species affected. It therefore contributes to a quick and reliable assessment of regional storm damage within only a couple of days. The tool was developed in PHP, a scripting language used for web development, and combined with MySQL database server. A Windows dedicated AMP (Apache-MySQL-PHP) solution stack is used to run the dynamic web site.

In addition, previous crises management operations must be debriefed (see i.e. Raetz, 2004), from both strategic and operational angles, and improvements integrated to a new version of the plan. There are thus several possible levers for revising the plan, even more when the organisation has implemented a quality management system. This review has to rely on a sound and robust approach. For windthrow contingency planning, a continuous improvement process is established based on Deming's Quality Management Delivery Model and its inherent principle of Plan-Do-Check-Act. This methodology allows continuous improvement of the WCP through successive steps (Figure 26).

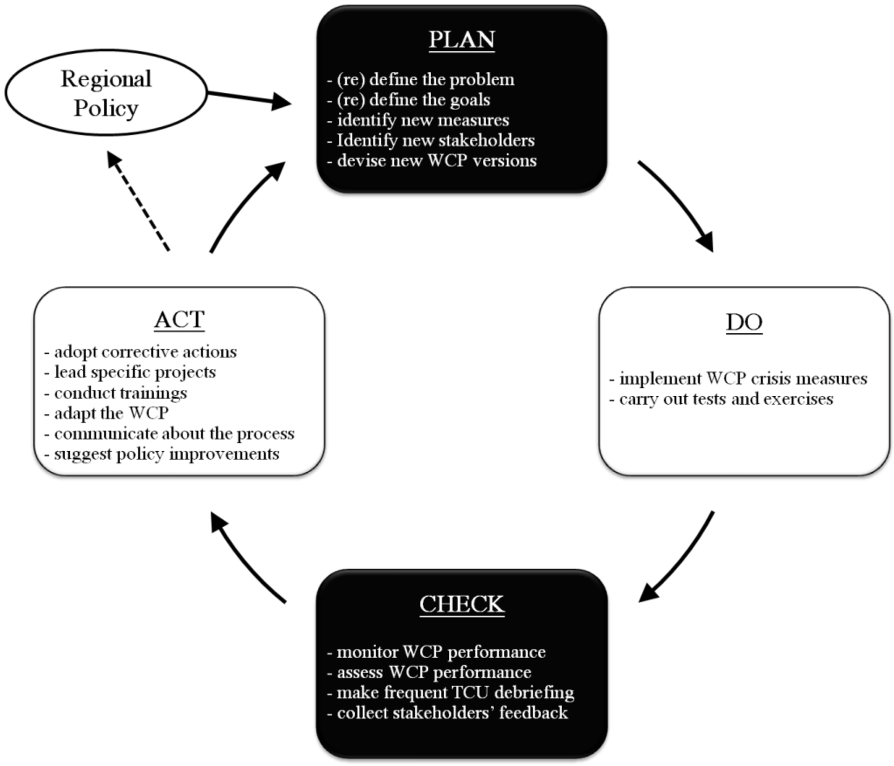

Figure 26. Deming's wheel applied to the Walloon windthrow contingency planning process

The planning step consists in a definition of the problem – storm impacts on forests – and associated goals, taking in account the policy context, as highlighted in a previous section (5.4.1). In a continuous improvement approach, context and goals, as well as measures and stakeholders, must be redefined each time the planning process take place. The output of this phase is a new release of the WCP. During the implementation step, WCP measures are carried out. In a real crisis management process, the whole plan is likely to be implemented. Otherwise, tests and exercises (see 5.4.4) that focus on specific measures must be carried out regularly for feeding the improvement process. Next step is to check plan performance and efficiency in order to take corrective actions. For this purpose, it is important to define criteria and indicators that could be used to measure performance and quality. It can be either qualitative or quantitative indicators, provided they are tangible and easily monitored. TCU members should also be frequently debriefed to learn about plan failures and success. Feedbacks from stakeholders not directly involved in the management process are also very insightful. Audits and quality surveys can help during this evaluation step. Learning from crises in other countries is also extremely valuable. The final step is to take corrective actions to improve the WCP performance. A kind of action could be to run specific projects to work out identified problems and consequently improve the plan implementation. Trainings could also help to enhance its implementation. If necessary, the WCP should be structurally improved. When issues are arising from the policy context, it is important to suggest policy improvement in order to make the plan efficient.

5.5. CONCLUDING REMARKS

Contingency planning is nowadays essential part of risk management systems in both private and public sectors. Contingency plans clearly contribute to enhance preparedness and response towards unexpected events, whatever their causes. In forestry, this concept is emerging; however, it often results from recent crises, not from a continuous improvement process. It was not the case for Wallonia, where no destructive storms stroke since 1990. Developed in the context of this PhD thesis, the Windthrow Contingency Plan is the result of the integrated strategy that we suggest for managing future windthrow events at the regional scale. Due to its pioneering nature, and consequently the lack of regional guidelines to rely on, we had to implement concepts from the theory of contingency planning for devising it. It could have caused misunderstandings with forest sector, which is not familiar with those somewhat abstract concepts. Furthermore, as there was no damaging event to assess its performance, there is still some reluctance from the end-users to involve in its daily improvement and maintenance. Nevertheless, trainings and exercises could help in this appropriation effort.

Third section

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Implementing strategic decisions: the case of timber storage

- Implementing decisions from strategic to operational level is a key step of windthrow crisis management. In this thesis, we'd liked to illustrate how it was possible to bridge this gap, through the example of timber storage.

- Among the portfolio of crisis management options accessible to decision-makers in the aftermath of destructive storms, timber storage is a proven effective lever for softening economic impacts of storms on the regional market and regulating industrial supply.

- The level of preparedness before the calamity and the ability to react quickly after the event, as well as the knowledge of technical requirements are key challenges for ensuring efficient timber storage strategy, particularly in regions that did not undergo severe storm damage for decades and thus where storage infrastructures and relying knowledge has therefore progressively disappeared, as in Wallonia (Belgium).

- Chapter 6 presents a GIS-based Decision-Support System developed for assisting regional planning of sprinkling storage by public authorities before and after a huge storm. Chapter 7 presents the results of a 5-year research about anaerobic storage of wood, an alternative to traditional conservation methods that could be used after a storm for local timber of high commercial value.

6 REGIONAL PLANNING OF TIMBER STORAGE

Storage of windblown timber is a key requirement for mitigating economic impacts of storms at the systemic level. It allows preserving wood from too rapid decay and quality depreciation, limiting the volatility of timber market and lowering the amount of feeding material in the neighbourhood of healthy stands. This section presents a methodology for planning timber storage at the regional level before the next huge storm and, in case of damage, for locating most suitable sprinkling storage terminals.

This chapter is a transcription of the following manuscript, submitted to *Biotechnology, Agronomy, Society and Environment* Journal (submission: 23/05/2016; acceptation with major revisions: 23/08/2016).

> RIGUELLE, S., JOUREZ, B., HÉBERT, J., PIROTHON, B. & LEJEUNE, P. A GIS-based decision-support system for locating sprinkling storage terminals for windblown timber.

6.1. INTRODUCTION

Severe winter storms are one of the major threats for forests in the world (van Lierop et al., 2015) and are considered as the most destructive abiotic agent of European forests (Thom et al., 2013). Destructive storms can be defined in many ways, depending on the stakeholders' perspectives and expectations towards forest areas and timber resource. From a meteorological angle, storms originating from extra-tropical cyclonal processes and generating maximum gust wind speed above 30 $m.s^{-1}$ are prone to cause extensive damage, mainly in winter (Gardiner et al., 2010). Even though the influence of future climate conditions on storminess remains ambiguous (Blennow and Olofsson, 2008), frequency as well as intensity of such events will likely increase in mid-latitudes in continental regions (Leckebusch et al., 2006), thus also in Central and Western Europe where higher surface wind speed (Fink et al., 2009) and shorter return-periods (Karremann et al., 2014) are expected.

Regarding European forest areas, this upward trend in windstorm severity combined to increasing exposure due to accumulating standing timber volume (Seidl et al., 2011) enhance the risk of severe winter storm losses (Schwierz et al., 2010). Destructive storms, which destroy in hours the equivalent of several annual harvests (Bründl and Rickli, 2002, Björheden, 2007), threaten economic, environmental and societal functions of forests ecosystems and consequently goods and services delivered to the society (Seidl et al., 2013). For instance, wind disturbances could offset national carbon storage strategies that cope on forests sinks (Lindroth et al., 2009). In planted and intensively managed forests, where the economic value at risk is high, such sudden disturbances often cause stumpage prices' collapse (Nieuwenhuis and O'connor, 2001a), and lead for owners to drastic financial losses (Moore et al., 2013), exacerbated by increasing costs for timber salvage (Prestemon and Holmes, 2004) and stand restoration (Schönenberger, 2002a). Imbalances in timber availability after huge storms propagate to industrial supply chain and affect market dynamics (Schwarzbauer et al., 2013). Every economic agent within the forest-wood chain is impacted in the long-run and has to adapt its procurement behaviours (Hartebrodt, 2004). Most of time, losses are only slightly compensated by public funds (Brunette and Couture, 2008). Whatever the perspective, systemic management of storm impacts is thus required at the regional and/or national level(s) to support the forest-based economy in its entirety (Riguelle et al., 2016b).

Among the portfolio of mitigation measures available to decision-makers in the aftermath of destructive storms, timber storage appeared during previous crises as one of the most effective lever for softening market impacts on the forest-based sector (Grayson, 1989, Peralta et al., 1993). Because storms have an impact on timber prices through volume and quality (Brunette et al., 2012), storage could have a double positive effect (Costa and Ibanez, 2005). On the one hand, by preserving the technological quality of timber that cannot be processed quickly, it allows mitigating the economic losses for owners and industrials. On the other hand, it helps regulating the supply on a longer time-scale and thus limits volatility of prices. Storage can also contribute to mitigate atmospheric carbon releases

(Zeng et al., 2013), and regarding phytosanitary risks, limit the exposure of still standing and healthy trees towards pests outbreaks.

However, several issues are arising when planning timber storage before and after a storm. Among strategic issues, one can highlight for instance the basic choice to store or to export (Caurla et al., 2015), the amount to store by type of species and the optimal storage duration. For those latter purposes, the use of systemic analysis tools could help decision-makers to assess storage effects on the dynamics of windblown timber supply chain (Riguelle et al., 2015a). Operational issues are also numerous: request of public authorizations, purchase and maintenance of material, hiring and training of staff, caretaking of terminals, *etc.* Between the strategic and operational questions, tactical issues, mainly logistics, are arising. The logistics of timber storage includes inbound and outbound features, encompassing operations from damage forest areas to terminals and from terminals to end-users (*e.g.* paper mills, sawmills, panel factory, energy plants). It involves many operations and actors for moving, stocking and caretaking of timber products and is therefore very costly. For instance, extra costs ranging between 12 and 20 €/m³ can be expected for a 3-year sprinkling storage (Liese, 1984, Costa and Ibanez, 2005). Despite the financial compensation often provided by public subsidies, these supplementary costs must be optimized to make timber storage cost-effective in the long term (up to 24 months). On the one hand, economies of scale can be enhanced by limiting the number of terminals and increasing the amount stored per terminal (Costa and Ibanez, 2005). On the other hand, as transportation accounts for a large part of stored timber prices (Murphy, 2003, Audy et al., 2012a), the distance covered by trucks and loading characteristics are important factors to handle. As for other timber supply chain issues, spatial arrangement of terminals in regards to transportation and infrastructure costs is thus a key challenge (Rauch and Gronalt, 2010, Kons et al., 2014). Nevertheless, it must also integrate end-users requirements and cope with road facilities and environmental constraints (*e.g.* protected areas).

The level of preparedness before the calamity and the ability to react quickly after the storm event are also key challenges for ensuring efficient timber storage strategy. It is particularly true in countries/regions that did not undergo severe storm damage for decades and where storage infrastructure and relying knowledge has therefore progressively disappeared. In Wallonia, the Southern region of Belgium, it has been identified as priorities to strengthen the storm damage risk management process (Riguelle et al., 2015a). In this context, it seemed important to bridge the gap between strategic decisions and daily operational management and therefore improve tactical management of storage operations before and after destructive storms. The aim of this study is to design a storage terminals network (STN) in Wallonia (Belgium) that could be activated, either partially or entirely, as soon as possible after a destructive storm, depending on the damage severity and their spatial distribution. This general purpose is handled in two steps with the help of GIS tools: (1) localization of potential terminals in Wallonia; (2) set up of a decisional framework for supporting decision-makers in the storage implementation process in regards of forest-based sector's requirements.

6.2. MATERIAL AND METHODS

6.2.1. Case study

The scope of this study is Wallonia, the Southern region of Belgium, where forests areas cover roughly 33 % (555.000 hectares) of the territory (Figure 27). About 87 % of these woodlands are dedicated to timber production (Alderweireld et al., 2015), for an overall annual harvest of roughly 4.000.000 m³. Whereas the forest surface remained stable between 1984 and 2015, the growing stock (GS) has increased from 25% during the same period (Alderweireld et al., 2015). This latter factor, which exacerbates the regional exposure to natural hazards, is only slightly counterbalanced by the continuous cutback of Norway spruce productive areas. As Norway spruce, which remains the prevalent species in volume (41 % of GS), and beech (9% of GS) are species prone to wind damage (Schütz et al., 2006), the susceptibility towards windthrow remains high. Furthermore, those species are also presenting poor natural durability features, according to EN 350-2 standard, which imply storing them rapidly after a storm. The study will particularly focus on Ardenne sub-region, which hosts 64 % of regional growing stock and delivers 85% of softwood production; mainly spruce (Figure 27).

From an end-users perspective, several industries that use round wood (logs or bolts) or by-products (wood chips) as raw material are located in Wallonia (Figure 27). Sawmilling units are mainly located close to forest estates, in the southern part of the region. According to regional statistics (OEWB, 2015), 2.500.000 m³ of softwood are sawn yearly in Wallonia, while hardwood sawing is very specialized (70.000 m³). The Belgian pulp, paper and panel sector (PPPs) consumes roughly 4.2 x 10^6 m³ of wood (expressed in round wood equivalents) per year, logs accounting for about a half in this amount (OEWB, 2015). PPPs industries are mainly located near the regional borders or outside Wallonia. Hence, only 18 % of the PPPs' total procurement is coming from the Walloon forest resource in normal times, the major part being imported mainly from France (67 %) and Germany (7%).

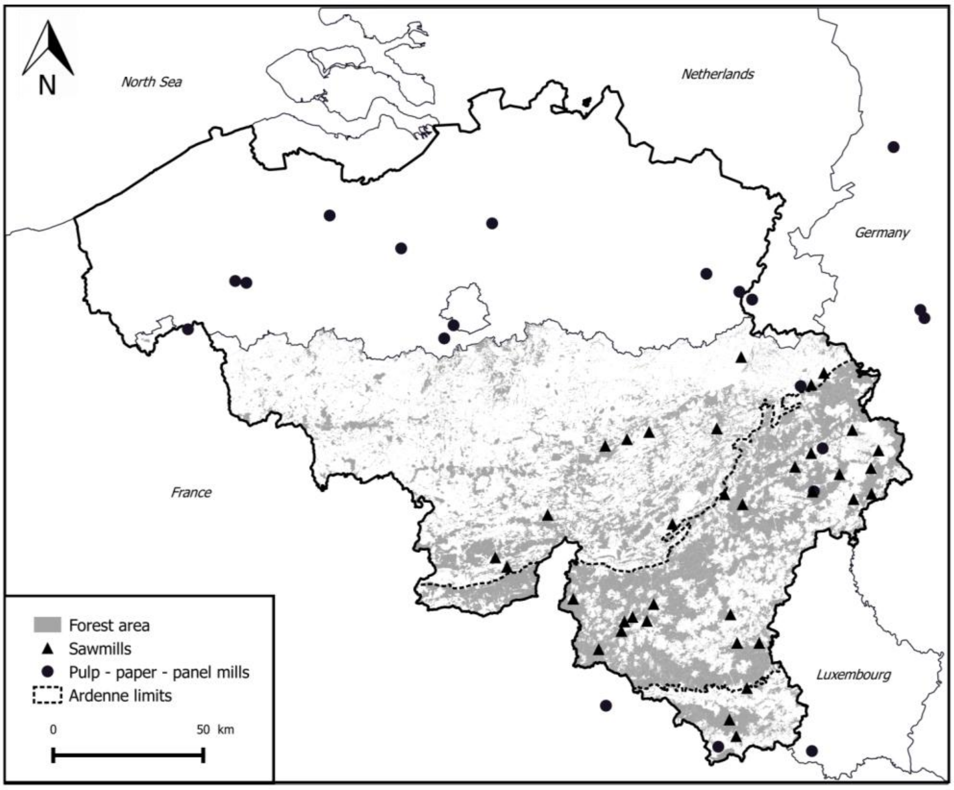

Figure 27. Forest area and major forest-based industries in Wallonia (Belgium).

6.2.2. Sprinkling storage requirements

A common method to store timber is to keep the moisture content of wood above a threshold value of 100 % and to maintain this level constant throughout the process in order to prevent wood degradation by fungi or insects (Peralta et al., 1993). Wet storage of timber can be achieved by either sprinkling (spraying with water) or ponding (immersion in water) it, but ponding was not considered in this study as it is very infrequent in Wallonia. In-depth description of sprinkling storage process and requirements can be found in several papers (Liese, 1984, Syme and Saucier, 1995, Pischedda, 2004). Beside soil and slope characteristics, one had to pay attention to land use features to minimize annoyance of surrounding population. Therefore, areas too closed to residential areas (distance inferior to 100 m) were excluded from network selection, considering that public authorizations will not be delivered in those places. In addition, protected areas – Special Protection Areas and Special Areas of Conservation, according to European Council Directive 92/43/EEC – have been removed. Finally, catchment, flood-risk and bathing areas must be avoided due to the potential impacts of sprinkling storage runoffs on both surface and groundwater (Hedmark and Scholz, 2008).

6.2.3. GIS input layers and parameters

ArcGIS 10.2 software (ESRI 2011) has been used to identify storage terminals. ArcGIS Model Builder was used for spatial analyses because it enables testing several parameters' values to calibrate and validate the model and running it several times in order to compare results. The model integrates parameters related to the sprinkling storage process as well as site and logistical constraints. Data are processed in raster mode, with a spatial resolution of 10 x 10 meters. Five layers related to land constraints (*SOIL, SLOP, LUSE, ECOL, and HYDR*), as well as two layers related to terminals' accessibility (*ROAD*, *WATE*) were used as input for terminals selection (see description in Table 6. ArcGIS input layers and parameters used for selecting terminals). Four parameters were also considered: the terminal's size characteristics (*site_area*, *site_width)*, the accessibility to the road network (*dist_road)* and the distance to an appropriated water supply source (*dist_wat).* For the present study, it was assumed that at least 10.000 m^3 of timber can be stored on average per hectare. This amount corresponds, for logs of 10 meters, to stacks of 3-meters high (Pischedda, 2004). In addition, terminals must present sides of at least 100 m wide and long for handling and cost efficiency purposes. Appropriated water supply sources considered in this study are watercourses characterized by a minimal watershed of 500 ha, which guarantee a minimal stream flow, and inland water body of at least 500 m².

Table 6. ArcGIS input layers and parameters used for selecting terminals

Name	Type	Description	Minimal requirement(s) for selection
ECOL	*layer*	ecological features	exclusion of protected areas
HYDR	*layer*	hydric features	exclusion of catchment, flood-risk and bathing areas
LUSE	*layer*	land use	exclusion of areas closed to residential zones (≤ 100 m)
ROAD	*layer*	watercourses/water bodies	watershed ≥ 500 ha, water bodies ≥500 m²
SLOP	*layer*	field slope	slope ≤ 2 % *or* ≤ 5 % *or* 7 %
SOIL	*layer*	soil type	exclusion of poorly drained and peaty soils
WATE	*layer*	roads network	exclusion of highways
dist_road	*parameter*	distance to closest road	exclusion of poorly drained and peaty soils
dist_wat	*parameter*	distance to water supply source	distance ≤ 100 m *or* ≤ 250 m *or* ≤ 500 m *or* ≤ 1000 m
site_area	*parameter*	minimal area of terminals	surface ≥ 2 ha *or* ≥ 5 ha
site_width	*parameter*	size requirements	site length and width ≥ 100 m

6.2.4. Selection of Storage Terminals Networks

The selection of suitable areas for sprinkling storage was done in three steps. In a first step, we choose to run several simulations corresponding to a range of initial values in order to highlight the impact of parameters on the results. Therefore, three values were tested (2, 5 and 7 %) for slope parameter (SLOP); for the minimal distances to roads (dist_road) and water supply source (dist_wat), four values (100, 250, 500 and 1000 m) were used; and finally storage areas of minimal 2 and 5 ha were considered (site_area). Consequently, 96 scenarios, corresponding to as many Storage Terminal Networks (STNs) were generated. Among those STNs, a screening was then done to keep STNs whose storage capacity is between 1 and 5 million m³. Indeed, this range of capacity allows flexibility in further selection processes. Finally, after an advanced selection of STNs based on the number of sites and their localization, a unique STN for Wallonia will suggested. Technically speaking, Boolean aggregation (Figure 28) was applied in ArcGIS to the five storage-related layers (SOIL, SLOP, LUSE, ECOL, and HYDR) for identifying areas where sprinkling storage is possible, from both technical and legislative angles (STOR1). This intermediate output layer was then combined with accessibility requirements (ROAD, WATE) in order to select areas where sprinkling storage is operationally feasible (STOR2). Then we applied consecutive selections to identify terminals matching with size and surface requirements. Finally, polygons were successively shrunk and expanded in order to clean up small erroneous data and generate a polygonal output layer containing storage terminals (STNi, with i being the order number of scenario).

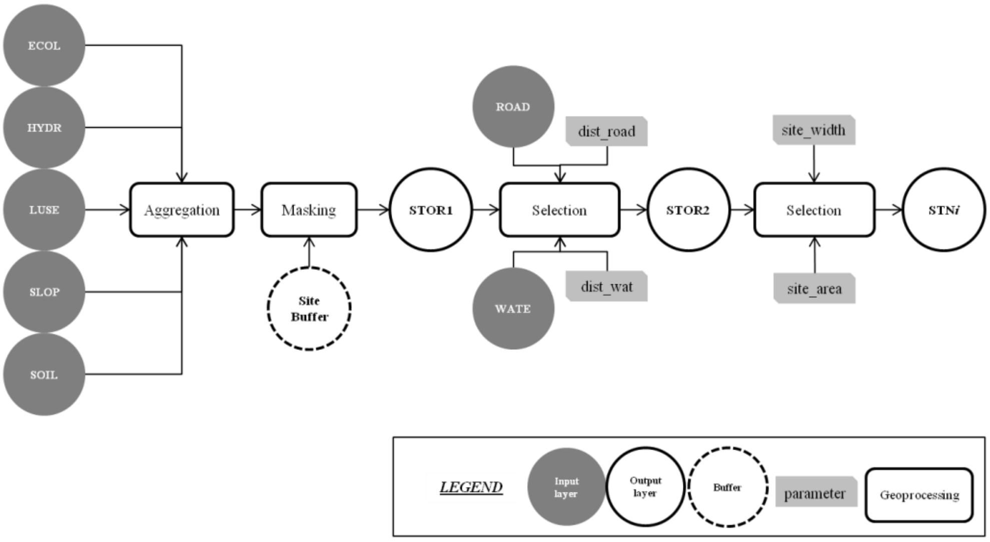

Figure 28. Conceptual view of selection process with ArcGIS Model Builder

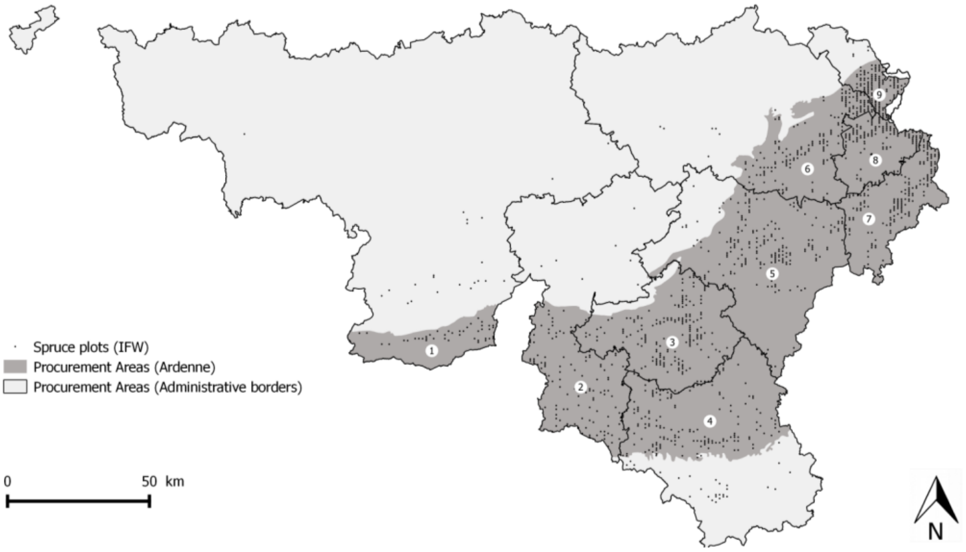

Figure 29. Procurement Areas and IFW plots where spruce is the dominant species in Ardenne sub-region.

6.2.5. Selection of storage terminals after severe windstorms

The additional goal of this paper is to support logistics of timber storage after huge storms by identifying most suitable storage places within this pre-established storage terminals network. Considering a hypothetic maximal damage of 8 million m^3 – equivalent to twice as much than regional annual harvest and 7% of the regional growing stock –, a total storage capacity ranging between 1 and 2 million m^3 is needed at the regional level. In order to determine which sites should be activated within the network, a repartition based on the damage level within sub-regional procurement areas (PAs) will be done. In Wallonia, wind damage data can be obtained through the regional forest inventory (IFW), a systematic network of 11.000 sampling plots, located in public and private estates. Whereas IFW network is initially used in the crisis management process to assess the amount of damage at the regional scale within a 72-hours delay (Riguelle, 2010), it may also serve for storage decision-making process, as it can deliver a sub-geographical repartition of damage for deciding in a first approach which terminals should be activated. In addition, nine Procurement Areas (PAs) were delineated in order to facilitate the selection after a storm (Figure 29). Procurement Areas were defined to generate homogenous zones in terms of timber supply while limiting distances. Most of those PAs contains between 10 and 15% of IFW sampling plots in which spruce is the dominant species (Table 7**Erreur ! Source du renvoi introuvable.**). Except for the Procurement Area n°1, whose extend is limited by national boundaries, it means that PAs are globally homogenous in terms of exposure to damage. PAs were also designed to minimize the maximum distance from forest areas to terminals, in relation with timber transportation constraints.

Table 7. Characteristics of Procurement Areas (PA) in the Ardenne sub-region

PA	IFW public plots	Share (%)	IFW spruce plots	Share (%)	Spruce density in IFW public plots (%)
01	231	7	42	3	18
02	578	18	128	10	22
03	575	18	190	14	33
04	542	17	163	12	30
05	360	11	186	14	52
06	359	11	174	13	48
07	253	8	172	13	68
08	161	5	137	10	85
09	170	5	123	9	72
TOTAL	**3229**	**100**	**1315**	**100**	**41**

6.3. RESULTS

6.3.1. Selection of Storage Terminals Networks

Results of pre-selection process are presented below (Table 8). According to the range of values tested for the slope (*SLOP*), the distance to water supply (*dist_wat*) and to main roads (*dist_road*) and the site area (*site_area*), 96 scenarios were generated. For 36 of them, none possible storage site was identified. Among the remaining 60 STNs, 12 are matching with the initial capacity criterion (1 to 5 million m^3). Scenario n°1, which corresponds to the less restrictive combination of criteria, is also presented in the Table 8. It can be inferred from this first selection that there is no optimal scenario minimizing all parameters. On the one hand, terminals can be selected close to water supply sources, but they will be of lower capacity on average. On the other hand, bigger terminals can be found either by enlarging the maximal distance to water supply and to main roads or by selecting steeper sites. It clearly demonstrates that decision-makers would have to make a trade-off between those parameters in order to find an optimal network in Wallonia. Indeed, it is important to define a unique network for Wallonia on which to focus on to prepare for storm damage management.

Table 8. Characteristics of selected Storage Terminals Networks (STNs): in italic, the less restrictive scenario; in bold, STNs matching with advanced criteria (number > 30; capacity million m^3 *> 2.5; mean capacity > 50.000* m^3*/site).*

Results of pre-selection						**Parameters**			
ref STN	Number of sites	Total area (ha)	Total capacity (Mm^3)	Mean area (ha/site)	Mean capacity (m^3/site)	SURF (ha)	SLOP (%)	WATE (m)	ROAD (m)
1	*3123*	*50486*	*504.86*	*16.17*	*161658*	*2*	*7*	*1000*	*1000*
68	23	124	1.24	5.40	54027	2	2	100	1000
28	17	127	1.27	7.48	74846	5	7	100	250
71	28	130	1.30	4.65	46549	2	2	250	500
44	40	162	1.62	4.06	40571	2	5	100	250
56	29	244	2.44	8.41	84059	5	5	100	500
67	**51**	**269**	**2.69**	**5.27**	**52676**	**2**	**2**	**250**	**1000**
59	**38**	**284**	**2.84**	**7.46**	**74641**	**5**	**5**	**250**	**250**
12	70	297	2.97	4.24	42424	2	7	100	250
40	**82**	**420**	**4.20**	**5.12**	**51185**	**2**	**5**	**100**	**500**
24	**47**	**428**	**4.28**	**9.10**	**91031**	**5**	**7**	**100**	**500**
70	**77**	**430**	**4.30**	**5.58**	**55806**	**2**	**2**	**500**	**500**
52	**47**	**446**	**4.46**	**9.49**	**94879**	**5**	**5**	**100**	**1000**

6.3.2. Identification of an optimal Storage Terminals Network in Wallonia

A way to define this “most optimal network” could be to select sites among the most relevant scenarios. For this purpose, six scenarios (STN 24, 40, 52, 59, 67, 70) were thus selected (see Figure 30 and Table 8, in bold) according to three criteria: the number of sites (minimum 30), the total capacity (up to 2.5 million m^3) and the mean capacity per terminal (up to 50.000 m^3). Those hypotheses are driven by the necessity to ensure flexibility at the regional level in case of storm damage. Indeed, decision-makers would need enough options to adapt the regional storage strategy according to the repartition and severity of damage (see section 6.0).

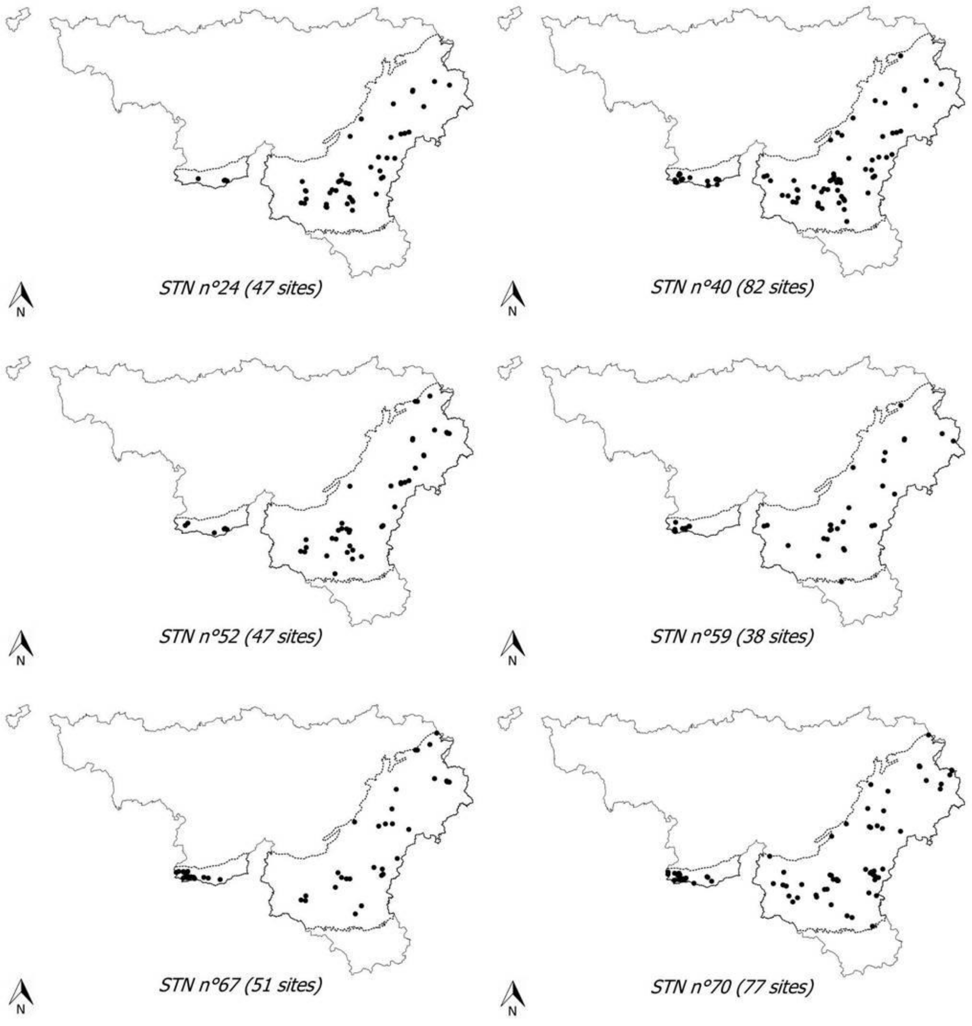

Figure 30. Maps of the 6 relevant Storage Terminals Networks (STN)

Those selected STNs have been merged with ArcGIS and duplicates eliminated. The final selection of terminals was done following three principles: *i)* terminals should be close to woodlands and surrounding forest-based industries; *ii)* terminals should be homogenously scattered across the studied area; and *iii)* storage capacity within each Procurement Area should be proportional to spruce plots' density within the IFW network. This latter step thus includes some manual selection by the user, with the help of ArcGIS. The result is a storage terminals network including 30 sites, for a total storage capacity of 4 million m^3 (Figure 31 and Table 9). Mean and median capacities are respectively 133 000 m^3 and 123 000 m^3.

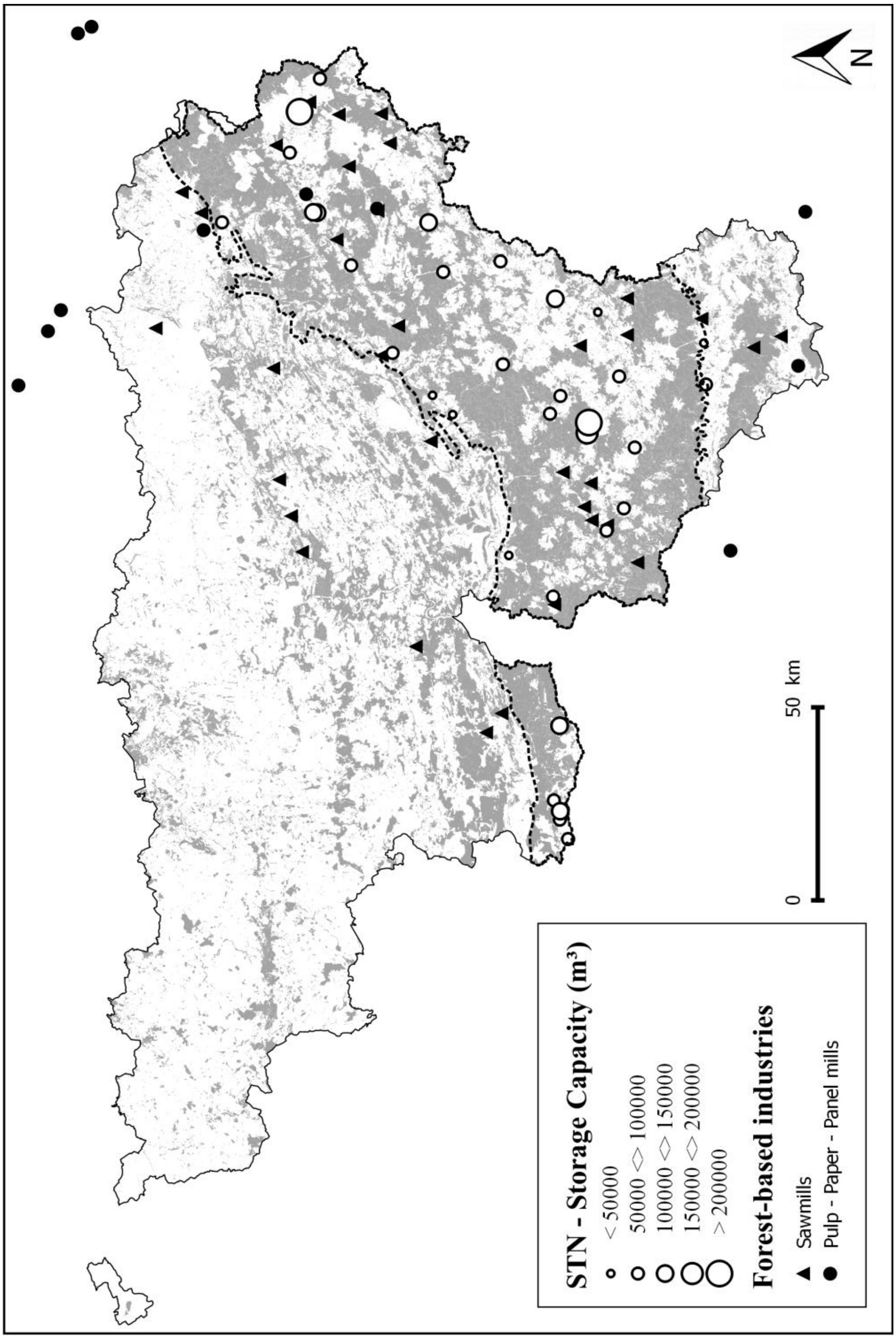

Figure 31. Suggested localizations for the 30 sprinkling storage terminals in Wallonia

Table 9. Storage capacity by Procurement Areas (PAs)

PA	Number of sites	Storage capacity (m^3)	Capacity share (%)	IFW spruce (%)
01	2	217400	5	3
02	3	356625	9	10
03	4	477390	12	14
04	4	500000	13	12
05	5	576800	14	14
06	5	549525	14	13
07	2	525675	13	13
08	3	442140	11	10
09	2	357675	9	9
TOTAL	**30**	**4003230**	**100**	**100**

6.3.3. Application to storage management in windthrow crisis context

In order to determine which site should be activated within the network and where, a simple decision tree was developed to support storage planning at the regional level (Figure 32). In this process, the total amount of damage estimated at the regional scale must be first disaggregated for each Procurement Areas ($PA\,i_{DAM}$). In the same time, a stocking target must be determined at the strategic level as well as the minimum amount per site (optional). This regional target, expressed as a percentage of estimated damage, is then applied to each PAs, following a pre-determined repartition method. Two repartition methods are suggested: in the first one (*balanced*), the aim is to reach a balanced repartition of sites at the regional level. In each PAs, terminals are successively selected according to their capacity, from biggest to smallest one. In the second method (*optimized*), the goal is to optimize storage capacity, whatever the localization of terminals. For both selection processes, the amount stored in each PAs cannot exceed the damage in this area, in order to limit transport distances. Figure 32 and Figure 33 present the results of the balanced and optimized selections.

In the following examples, underlying hypotheses are:

- an overall damage of 8.000.00 m³ ;
- damage are homogenous and proportional to spruce plots density within each PAs ;
- the total amount to store is 2.000.000 m³ (25% of initial damage) ;
- a minimal amount of 100.000 m³ per storing site.

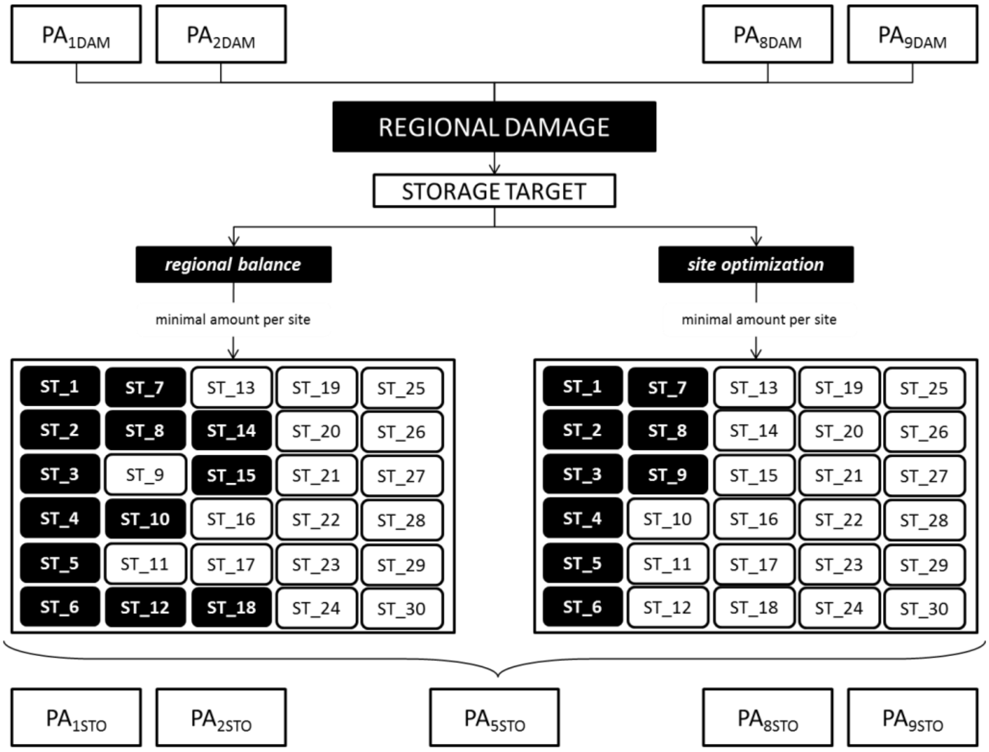

Figure 32. Framework for terminals' selection after windstorm, where PAi_{DAM} *and* PAi_{STO} *are respectively the damage and the amount to store within the Procurement Area i*

In the optimized process, the nine bigger terminals are selected and completely filled, except for terminal n°9 where 16 % of the capacity is still available. Globally, 98 % of storage capacity is used in the selected terminals. As high-capacity terminals are homogeneously located in the Ardenne, there is at least one terminal selected in every PA, except for PA1 where the minimal capacity is not reached. The balanced selection process led to a final selection of 13 terminals, and among them, only five are completely filled. Subsequently, the global capacity used reaches only 80 %. However, the higher density of terminals diminishes the mean transport distance within the network. Those results highlight that other parameters should also be taken in account in the selection process, especially trade-offs operational and transportation costs.

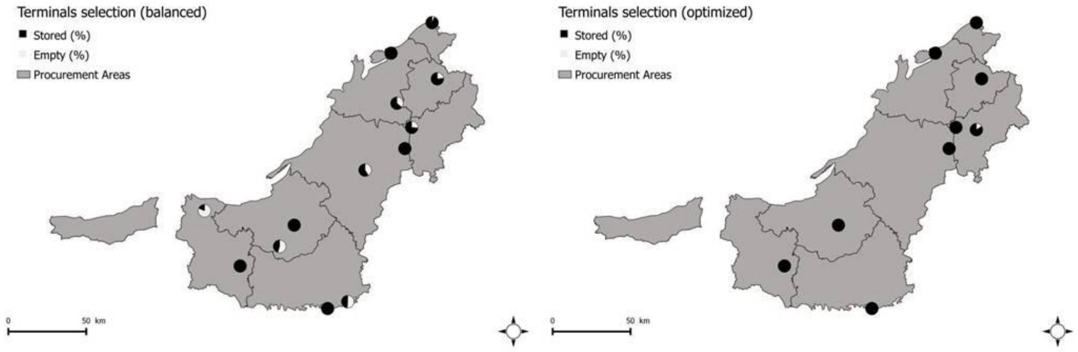

Figure 33. Illustration of sites selection process after windstorm in the study area: on the left, outcome of a balanced selection (13 sites), on the right, outcome of an optimized selection (9 sites)

6.4. DISCUSSION

This paper suggests a framework and a methodology to address storage planning and logistics at a regional level. The methodology exposed in this study allows identifying sprinkling storage sites that match with common strategic and operational requirements. Preliminary results show that theoretical locations of sprinkling storage terminals are numerous in the Ardenne sub-region, leading to high storage capacity. Nevertheless, none optimal network can be identified directly through the GIS-based modelling process. Advanced optimization processes and spatial operations are still needed to select an optimal network. Whereas the whole process is not computerized, it may be preferable to let ultimate trade-offs in the hands of decision-makers involved in the storage strategy. It should also be noticed that results were only partially validated in ArcGIS by checking coherence with topographic maps and satellite images. Therefore, it would be necessary to carry on field validations to corroborate initial selection. On the one hand, it is mandatory to check discrepancies between the GIS outputs and the reality, for instance changes in watercourse tracks or land use changes. On the other hand, it is necessary to check hiring and financial feasibility with owners.

The network suggested in this paper also ensures flexibility in storage strategic management after huge storms in regards to capacity and costs. Furthermore, the study also helps public and private decision-makers to manage timber storage after destructive storm. Indeed, final selection of sites in the course of windthrow crisis management could be facilitated by walking through the decisional tree proposed in this paper. Whereas the Procurement Areas (PAs) approach is limiting, as it does not encompasses other risk components as the storm intensity and trajectory, the economic value at risk and the stands' susceptibility to damage, it enables identifying quickly within the network the top-ranked sites. This ranking could be improved through the establishment of a 'site quality index' that could combine site characteristics like capacity, distance to road network and to water supply, and slope. However, such index implies assigning relative values to and ranking those parameters.

In addition, other operational issues have to be kept in mind. For instance, as revealed previous crises, timber transportation would probably be one of these key logistical issues to deal with after severe storms. As an illustration, transportation capacity is often lacking after the storm (Bourcet et al., 2008) due to truck availability and road legislations. On the one hand, public authorities are bound to increase transport capacity to avoid a major bottleneck in timber mobilization at the regional level, but they have to make it with global strategy in mind, for example storing or exporting timber (Caurla et al., 2015). On the other hand, an optimal routing of round wood between storage terminals and industries is required to limit transportation costs (Bergdahl et al., 2003). For this latter purpose, decision support systems could assist decision-makers in optimizing transportation flows (Forsberg et al., 2005, Andersson et al., 2008). Timber bartering or backhauling (Carlsson and Rönnqvist, 2007) are also important to consider if the transport capacity is lacking. Regarding those issues, the use of Procurement Areas as sub-regional storage management units is certainly an easy way to address routing and transportation issues.

After a severe storm, the main challenge for industries lays in quickly adapting and securing their supply chains according to new market conditions

(Björheden and Helstad, 2005). Here again, decision support systems based on Operational Research models can help industrial users to identify new strategies, including timber storage in terminals (Epstein et al., 2007, Broman et al., 2009). Nevertheless, as companies' logistic planning has to be changed over a few days to ensure procurement, the storage conditions should be known by advance, and such pre-defined regional storage strategy can comfort them. In addition, the involvement of industries in the storage effort, which would be conditioned by costs of operations, is also crucial for the success of the public strategy. In this context, we believe collaborative logistics within the forest-based sector is definitely a key element to enhance in the future in order to reduce storage and transportation costs (Frisk et al., 2010). However, as illustrated by Audy et al. (2012b), a framework is required to implement collaboration between regional stakeholders, and the public authorities should actively contribute to its definition, especially if they mainly fund storage operations. One may cite for instance the central issues of stocking and destocking logs that belong to several owners without financial prejudice.

As a conclusion, we believe this kind of work contribute to increase preparedness of decision-makers from both public and industrial side towards future storm events. Nevertheless, pro-active management of operational issues (permits, facilities) remains necessary to guarantee a quick implementation of storage strategy. Furthermore, in the context of an integrated storm crisis management process, collaboration of stakeholders within the forest-based sector is undoubtedly a key factor to enhance in order to reduce storage and transportation costs and make the strategy advantageous for each of them. Timber storage strategy must be view in this context as one part of an integrated and systemic management developed at the regional level for alleviating storm impacts on the forest-based sector.

7

INFLUENCE OF ANAEROBIC STORAGE ON WOOD PROPERTIES

Conservation of timber under anaerobic atmosphere is quite recent and its impacts on the mechanical and physical properties of wood are few described in the literature compared to sprinkling storage. Beyond the technical issues addressed in this section, we'd like to illustrate that offering sound operational solutions to the forest community is also crucial for integrated management of storm damage risks.

This chapter is a transcription of the following paper:

> RIGUELLE, S., LESIRE, C., HÉBERT, J. & JOUREZ, B. 2016. Influence of a long-term storage in anaerobic conditions on Norway spruce (*Picea abies, L. Karst.*) physical and mechanical wood properties. *Wood Material Science & Engineering*. Doi: 10.1080/17480272.2016.1178668.

7.1. INTRODUCTION

Timber storage is a central issue in forestry. Under normal market conditions, storage duration is very short and thus the raw material quality is maintained. However, when the forest-wood chain is disrupted, for instance after huge storms (Björheden, 2007), the forest-based sector is unable to absorb the amount of damaged timber within a reasonable delay in regards to wood decay dynamics. As a consequence damaged trees are exposed to fungal or insect attacks and to physical changes unless they are treated or stored under special conditions (Ruel et al., 2010). Stain can lead to severe loss of esthetical value (Jonsson, 2013), whereas decay causes a loss in wood quality through the degradation of cellulose and often also of lignin (Schmidt, 2006). By preserving the technological quality of timber that cannot be processed quickly, storage allows mitigating economic losses for owners and industries. In addition, it can help regulating the supply on a longer time-scale and thus limiting prices' increases for the industrial sector (Costa and

Ibanez, 2005). Recent destructive storms highlighted the role of storage in regulating the supply chain functioning for saving money (Grayson, 1989, Peralta et al., 1993, Valinger et al., 2014) and storage progressively arises as one of the main strategic issues in mitigating storm impacts on forest-based economies.

This challenge implies to know what are the pros and cons of traditional storage methods in regards to the industrial targets. Traditional storage methods usually include the conservation of storm-felled timber on site (live storage), or the storage of logs and bolts under wet or drying conditions (Pischedda, 2004). On-site storage aims at differing harvesting of trees with a sufficient anchorage or located in shaded areas. It is assumed that moisture content of trunks will decline slowly in these specific conditions and will preserve trees from insect and fungi attacks (Jonsson, 2007). This storage is suitable for species with high natural durability, for instance Oak or Douglas fir, but not for more sensible species as Beech (Flot and Vautherin, 2002, Vinkler and Alzingre, 2003). Norway spruce trees with roots still partially connected to the soil are able to survive one year without any loss of quality and value (Blom and Thörnqvist, 2014) before starting to dry significantly and to decay (Jonsson, 2008). Nevertheless, maintaining damaged Spruce trees in forest is risky regarding the potential hosting of bark beetles and parasitoids in non-harvested windthrow areas from the second summer (Wermelinger et al., 2013).

Timber storage in dry or wet conditions is thus recommended for longer periods, either on dedicated terminals or log yards. Wood storage in drying conditions implies to reduce its moisture content under a 20% threshold which does not enable fungal or insect degradation. Debarking speeds up the drying, but unprotected logs are exposed to cracks, blue stain and rot (Jonsson, 2012a). On the contrary, log storage under wet conditions aims to saturate the wood to above 100-120% of moisture content to prevent fungi and insects establishment during the process (Powell et al., 2000). From a technological point of view, wet storage is known to improve the impregnability of wood (Singh et al., 2009). The loss of strength resulting from wet storage seems to be negligible but variations in the elastic properties have been noticed (Efransjah et al., 1989). Sprinkling is the more common method for storing large amount of timber in the aftermath of catastrophic storms, because of its efficient protection against drying, cracks, fungal or insect degradations (Lind et al., 2004) and the huge storage capacity by unit of surface. However, this method presents several disadvantages: huge energy and water consumptions (Liukko and Elowsson, 1999, Latour et al., 2009) and severe environmental impacts due to the polluted run-off water (Hedmark and Scholz, 2008, Jonsson, 2012b). Wastewaters contain some toxic compounds , such as phenols and carbohydrates (Borga et al., 1996), and consequently must be handled to comply with state requirements (De Hoop et al., 1998).

Anaerobic storage is another way to protect timber against decay agents without any environmental constraints. Among specific anaerobic storage methods, the patent US 6,830,727 B1, relating to: “a method for stocking and preserving green round wood and sawn timber” (Mahler et al., 1998), presents an advanced method where timber is bundled within a double layer of polyethylene tarps. In this process, the oxygen inside the silo is decomposed by respiratory processes of fungi, bacteria and wood cells, forming CO2 and H2O. In a very short time, fermentation processes convert hemicelluloses and saccharides into organic acids and CO2 and oxygen rate drops quickly. The oxygen content must stay all the time under a 2% threshold to guarantee an optimal conservation. Knowledge about wood properties evolution throughout the process is not very abundant. Maier (2005) presented results about moisture content and visual aspects of wood stored through this specific process, but did not address wood mechanical and physical properties. Older experiments on Beech wood stored in log stacks covered with plastic tarps revealed no degradations for up to six months (Schadelin, 1970, Anderson, 1972). Moreau and Barré (2010) also highlighted good levels of conservation for Beech wood stored in unsealed and sealed silos, but only from a qualitative point of view.

Unlike wet storage, anaerobic storage is thus few described in the literature, and the forest-based sector is lacking information about its effects to balance costs and market opportunities. Whereas the process is known to be functioning, temporal evolution of properties is also lacking, especially regarding the undefined ‘long-period’ claimed in the patent (Mahler et al., 1998). In this context, the paper aims at investigating the effects of a long-term anaerobic storage process on visual, physical and mechanical properties of Norway spruce, by comparing samples that underwent anaerobic storage (stored logs) or not (control logs). The paper presents first the sampling as well as the mechanical and physical tests selected. Results are then discussed in regards to pre-cited objectives.

7.2. MATERIAL AND METHODS

7.2.1. On-site experiment

In order to build the experimental sealed silo, 75 cubic meters of Norway spruce (*Picea abies* (L.) Karst) were felled in the area of Eupen in Eastern Belgium in May 2008. The 20 m logs were stored under anaerobic atmosphere according to the patented method described in Mahler et al. (1998) and Mahler et al. (1998), Maier (2005). The logs were stored immediately after felling. Decaying or rotten parts were purged from the trunks in order to prevent any contamination in the airtight enclosure. The silo was covered with a net to strengthen and protect the structure against degradations from wild animals and climate. A control valve was installed before welding the tarps to allow controlling the internal atmosphere. During the first days, oxygen and carbon dioxide rates were measured twice a day and then weekly measurements were done, using a gas analyser with an internal pump (Anagas CD98HR+ with 0.5 % of tolerance for O2 measurement). During the trial, the oxygen rate always stayed under the critical 1 % (+/- 0.5 %) threshold, and after a peak in the first weeks, CO2 rate stabilized around 15 %. No tear or damage was noticed during the experiment. In regards to these parameters, the logs were supposed to be totally preserved from fungal and insect attacks when the silo was opened on February 2013, after 57 months of storage.

7.2.2. Sampling

The testing material was selected among the 75 m^3 of Norway spruce. Five logs were randomly chosen in 2008 before sealing the tarps. A length of 2.8 m was cut in the butt log of the five trees. These logs were sawn in planks and stored in optimal conditions for natural drying under shelter. This experimental material is named below as “control logs”. Once again, when opening the silo in 2013, five logs of 2.8 m were cut on the same trees, in the extension of the first ones. After being sawn in planks, they were stored under shelter. Those samples are named below as “stored logs”. The logs were sawn following the same pattern to produce normalized test samples, as illustrated on Figure 34.

To allow comparison of stored and control logs coming from the same tree, samples from the closest zone of the tree have been chosen, in order to limit the variations due to the height Figure 34a). In the 2800 mm long logs, a central plank 85 mm thick, containing the pith, was first cut perpendicularly to maximum radius, and then divided into two half-planks along the pith (Figure 34b). For mechanical tests on clear wood specimens, the half-planks were sawn, starting from the pith and parallel to the grain, into three 30 mm thick battens, which were cut afterwards into chunks and then into bars. According to NBN 225 (1956) requirements, only two bars showing a straight grain, without knots or defects, were selected and planed to the final dimensions of 20 mm thick, 20 mm width and 300 (or 360) mm long (Figure 34c).

For mechanical tests on lumbers, pieces of 38x100 mm² section and 2200 mm length were sawn from the above mentioned half-planks and from complementary lateral planks. In continuation of these lumbers, specimens were cut off to achieve colour analysis (Figure 34b). The sawing pattern allows colour tests on flat sawn as false-quarter sawn specimens. Another lateral plank was sawn into 50 mm thick battens, from which three 750 mm long bars were selected for the impregnability test. Wood specimens were stored at standard atmosphere of 20 ± 2 °C and 65% ± 5% relative humidity in order to stabilize them around 12% ± 1% of moisture content, except for the specimens used for the impregnability test. These last were stored at atmosphere of 20°C and 76% relative humidity to reach the moisture content requested by CEN/TR 14734 standard (between 13% and 18%).

Due to the limited sampling, the study focused on three major mechanical properties: the modulus of elasticity in static bending, the static bending strength and the dynamic bending strength. Bending tests on clear wood specimens were carried out using an Instron 5500 series testing machine. Trials on lumbers were performed using a four-points bending machine. In addition, the following physical parameters were studied: moisture content just after the silo's opening, density at 12% moisture content, impregnability and colour variation. All the tests were performed according to standard procedures (see Table 10).

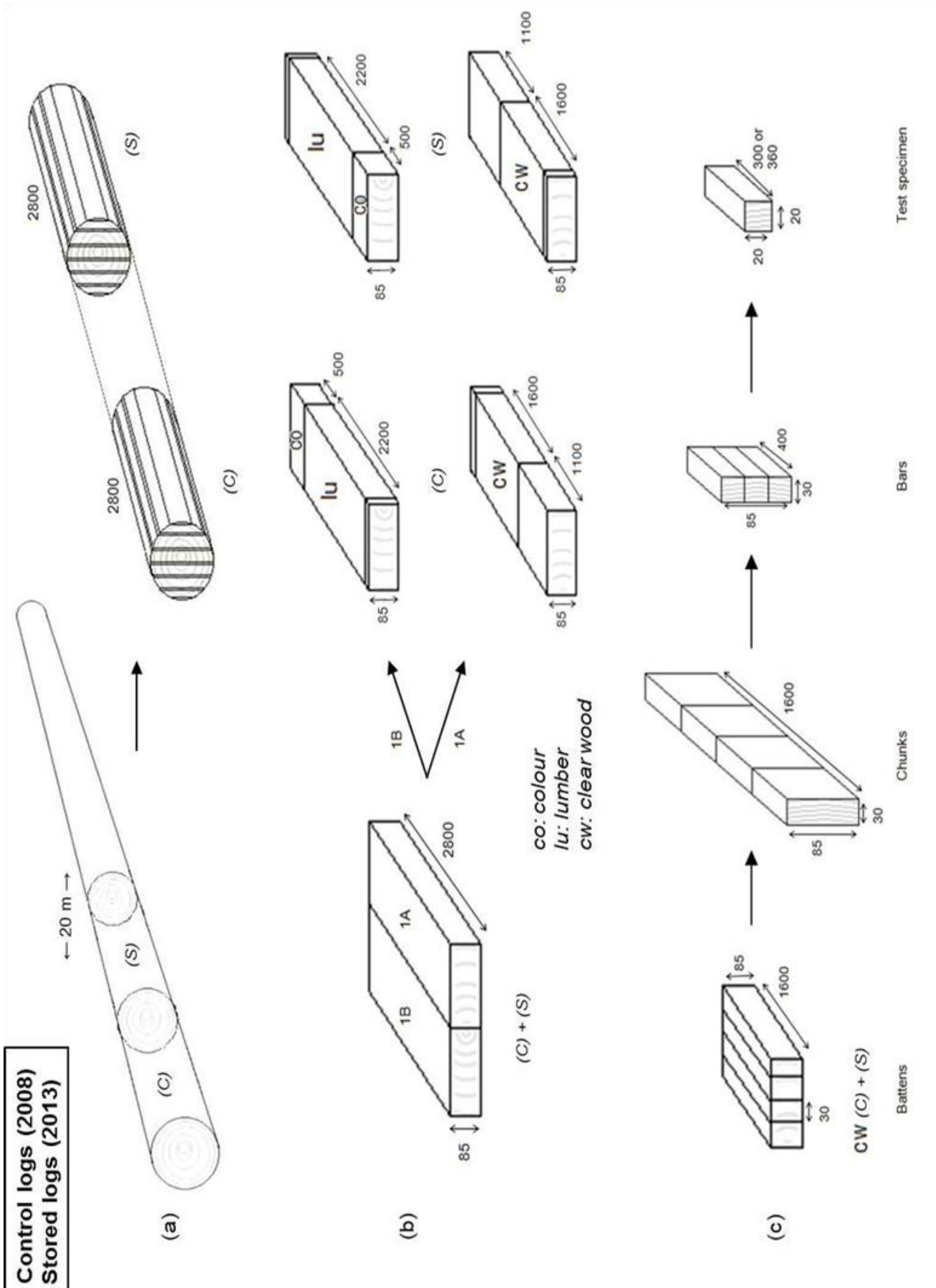

Figure 34. Sawing pattern of test samples (dimensions expressed in millimetres, unlike specified units)

7.2.3. Physical properties

The moisture content (MC, %) of logs just after the opening of the silo was determined through the desiccation of slices cut in the five experimental trees for three distinct axial positions (near the pith, half-radius and near the bark). The density at 12 % moisture content (ρ_{12}, kg.m^{-3}) was determined by measuring the clear wood samples' dimensions with a digital calliper and weighting them with a high precision balance.

Table 10. Characteristics of samples (type and size) and standards used for experiments

Test	**Type**	**Size (mm³)**	**Standards**
Modulus of elasticity	CW	360x20x20	NF B51 016
	L	2200x38x100	EN 408
Modulus of rupture	CW	360x20x 20	NF B51 008
	L	2200x38x100	EN 408
Resilience	CW	300x20x20	NBN 225
Impregnation	-	750x40x40	CEN/TR 14734
Colour	-	400x85x20	EN ISO 4120

CW: clear wood, L: lumber

7.2.4. Mechanical properties

For clear wood specimens, tests were carried on using Instron 5582. The modulus of elasticity in static bending (E, MPa), which provides an assessment of the wood stiffness was determined by a four-point bending test in the pure bending zone. The deformation was determined over a load range of 200 to 600 N applied at two points parallel to the rings. Static bending strength (σf, MPa) represents the maximum load the wood can support temporarily before breaking. Specimens are gradually loaded at two points parallel to the rings at a constant speed of 300 N.min-1 until it breaks. The dynamic bending strength, or resilience (K, J.cm-2), quantifies the energy required to cause the sample's break. This test was carried out with a pendulum machine test whose hammer thumps the specimen at its centre along the tangential direction. Mechanical tests were also conducted on lumbers, also using a four-point bending test. The global modulus of elasticity (EG, MPa) reflects the stiffness of the whole lumber. Distance between the support points was 1600 mm and loading points were positioned 600 mm from these. The load is applied at a rate lower than 0.114 mm per second. For each lumber, three repetitions were done: a blank test for which the value was observed, followed by two successive tests for which the values were recorded and the mean calculated. If, during a test, sensors marked a 10% difference, a third one had to be implemented. For global static bending strength (σfG, MPa) measurement, the load should be reached within 300 ± 120 s. Statistical analyses were carried out with Minitab 17.1.0. ANOVA was used to determine the storage effect on each mechanical parameter. These analyses were realised using a mixed model where the storage and radial position factors were specified as fixed and the tree factor as random. The radial position was determined on the original batten of clear wood specimens; however, the lumbers' analyses cannot take into account the radial position factor due to the sawing pattern. Selected confidence level is 95 % ($\alpha = 5$ %).

7.2.5. Impregnability

Due to the non or poorly impregnable feature of Norway spruce (classes 3-4 according to EN 350-2) and the proven impact of wet storage on this parameter (Singh et al., 2009), it also seemed interesting to find out the possible change of impregnability resulting from anaerobic storage. Impregnability parameter expresses the capacity of wood to become impregnated, for instance with preservation products, which is of main importance for industry. According to CEN/TR 14734, the specimens were coated at one end with an inert coating (Epoxy Speedcoat-SC™) and put in an impregnation chamber with no contact between them. After creating an artificial vacuum in the chamber during 45 minutes, a 5 % solution of copper sulphate pentahydrate (Cu.SO4.5H2O) was introduced in the chamber. This chamber was then pressurized to 900 kPa for 120 minutes. After the impregnation cycle, a sample of 100 mm is cut and the remained specimen is split in two. An indicator in solution (Chromeazurol-S™) is applied on the transversal and longitudinal sections. Minimal, mean lateral and minimal longitudinal penetrations were measured on specimens to determine impregnability class (Figure 35). In order to test the homogeneity of variables, statistical analysis on impregnation measures was completed with a Pearson's chi-squared test with a confidence level of 95 %.

Figure 35. Measure of minimal lateral (P.min), mean lateral and minimal longitudinal (d) penetration of copper sulphate in wood samples (adapted from CEN/TR 14734 (2004)).

7.2.6. Colour

The colour of sawn timber is also an important feature for wood industry in a competitive and dynamic market (Sandoval-Torres et al., 2010). In respect to that, the colour variation between control and stored trees was investigated, using a triangle test in respect to EN ISO 4120:2007 standard. This qualitative testing approach, more representative of the perception of the human eye, has been preferred to quantitative approaches using a spectrophotometer. Observations were carried out in a light-controlled environment, using a frame with three windows (70x70 mm^2) to present three side-by-side specimens to assessors. Within the three specimens, at least one was a control or stored sample. These triplets were generated randomly before the tests. Assessors had to choose among the triplet the sample whose colour seemed in their view the most different from the others. This protocol was carried out four times, for flat and false quarter sawn boards with and without planning, as the sawing patterns may change the colour perception of the wood. Overall, 30 observations were done for each sawing pattern by ten assessors from the laboratory staff. The statistical analysis of the colour tests was realised comparing the number of correct observations – a correct observation corresponds to a distinction made between control and stored samples – to the minimum number of correct observations required to conclude a significant difference between stored and control samples. On the basis of a binomial distribution, this minimum number is 15 at a 5% α-risk level.

7.3. RESULTS

The tarps remained in a perfect state during the experiment. When opening of the tarps, the logs presented a fresh aspect, similar to recently cut wood. The determination of mean moisture contents - 140 % just under the bark, 50% at half-radius and 41% near the pith - supported this first impression of freshness. In addition, some spruce logs stored under anaerobic conditions from 2008 to 2013 were still presenting an unforeseen freshness in 2016 compared to spruce logs recently harvested. The wood was exempt of cracks and the bark was still adhering. The silo revealed an unpleasant smell, probably due to anaerobic biological processes. However, the most frightening statement was the presence of a white mould on some parts of the logs. The causing agent appeared to be *Gliocladium solani*, an antagonistic fungus frequently observed on wood piles stored in anaerobic conditions through this process (Metzler et al., 1993, Maier, 2005). However, the mould stayed on the bark and did not affect the wood. After drying, the under-bark colouration measured on both extremities of each stored logs was varying between 14 and 28 mm.

Table 11 shows the results of mechanical tests on clear wood specimens and lumbers. Due to a significant difference of age and ring width between logs coming from experimental tree n° 4, it has been excluded from the statistical analyses. It can be explained by a numbering error during the logs' marking. Mean values and associated standard variation (SD) are presented for stored and control logs. Reference values found in the literature for Norway spruce grown in the same site conditions are also presented (Jourez and Leclercq, 1994, Hébert et al., 2002). Results reveal slightly lower values for mechanical properties of logs stored under anaerobic conditions, except for the modulus of elasticity measured on lumber specimens (E_G) compared to control logs. Density and resilience values are quite similar for both studied samples (variation smaller than 1%). Compared to the literature, mechanical properties of stored and control logs are in line with expected value for trees which have grown in same silvicultural and site patterns. Referring to the static bending strength of boards, the characteristic value is 24 for stored logs and 29 for control logs. The EN 338 ranks them in strength classes C_{24} for a structural use. Table 11 also presents the p-values resulting from the analysis of the variance (ANOVA) conducted to determine the possible effect of storage on wood properties. It reveals no statistically significant effect of anaerobic storage on studied properties (P values > 0.05) at both clear wood and lumber levels.

Table 11. Physical and mechanical properties of stored and control samples of Norway spruce; n is the number of samples; standard deviation shown in parentheses.

Parameter	**Stored**			**Control**			***P-values***		**Literature**
	n	Mean		*n*	mean		STO	STO*Rad	
Clear wood									
Density (kg.m-3)	*48*	484	(66)	*48*	480	(68)	0.521	0.760	431[a]
E (MPa)	*24*	13775	(2975)	*24*	14119	(2888)	0.657	0.288	11000[a] 14420[b]
σ_f (MPa)	*24*	90	(18)	*24*	93	(20)	0.662	0.274	71[a]
K (J.cm-2)	*24*	4.3	(1.1)	*24*	4.5	(1.1)	0.295	0.310	4.5[a]
Lumbers									
Density (kg.m-3)	*24*	488	(63)	*24*	493	(53)	0.260	-	341[a]
E_G (MPa)	*24*	12207	(2204)	*24*	11470	(2351)	0.113	-	10400[a]
σ_{fG} (MPa)	*24*	40	(10)	*24*	43	(11)	0.089	-	36[a]

[a] Hébert et al. (2002) [b] Jourez and Leclercq (1994).

Figure 36 shows the distribution of stored and control specimens in impregnability classes. Classes 3 and 4 are grouped because of the undetectable difference between these two classes for Norway spruce without specific investigations. More than the half control samples (54 %) are part of classes 1 and 2 while this proportion drop to 40 % for stored samples. Very few stored samples (7 %) are classified as easily impregnable (class 1). In accordance with the literature, those results confirm that Norway spruce is moderately or poorly impregnable without any pre-treatment. Furthermore, they highlight that anaerobic storage does not improve the impregnability of Norway spruce. On the contrary, it seems to worsen the situation. Nevertheless, result of the Pearson's chi-squared test performed on the data (2.16), is inferior to the theoretical value measured for a α-risk level fixed at 5% and 2 degrees of freedom (5.99), which attest that storage conditions and impregnability are independent for the studied sample. In other words, the relative frequency distribution is not significantly different between stored and control samples.

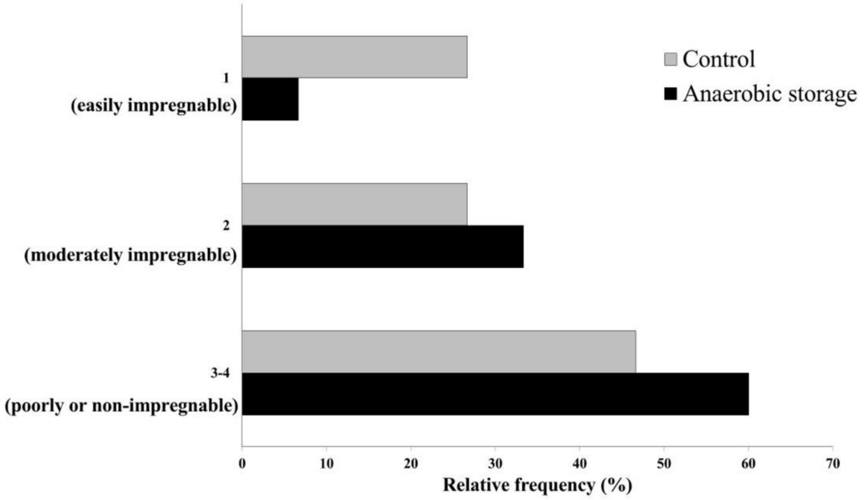

Figure 36. Frequency distribution of control and stored specimens among impregnability classes.

Table 12 presents the results of colour triangle tests for the four sawing patterns (flat and false-quarter sawn specimens, with and without planning) for a 5% α-risk precision level. Results reveal that no perceptible colour difference can be detected between wood stored in anaerobic conditions and control logs. Indeed, the number of positive observations is always inferior to the theoretical threshold for the four sawing patterns.

Table 12. Colour test – Number of correct observations by type of sawing patterns. The threshold value is the number of correct observations requested to conclude a colour difference between control and stored samples for a level α=5 of precision.

Sawing patterns	Correct observations	Threshold (α =5%)
Flat		
Planed	13	15
Non-planed	10	15
False-quarter		
Planed	8	15
Non-planed	10	15

7.4. DISCUSSION

The paper aimed first to assess long-term influence of anaerobic storage on Norway spruce's physical and mechanical properties. According to previous results, Norway spruce logs could be stored homogeneously under anaerobic conditions for up to 48 months without any danger for further industrial use. This is particularly insightful in a post-storm crisis context, where such delays are requested before timber market recovers. Longer anaerobic storage does not influence significantly wood internal properties, and consequently allows large range of industrial usages. However, the stored logs did not come from a damaged stand, although windblown trees may present internal failures that could affect these properties.

As expected, the process maintained the green aspect of logs, which is also important for industrial purposes although it may imply to process destocked logs rapidly to prevent further degradations (Maier, 2005). On the other hand, permeability to preservatives is not improved and timber products will still request suitable pre-treatments before impregnation to achieve deeper penetration and higher retention of preservatives (Pánek and Reinprecht, 2008). Finally, no colour modification was perceived by observers. Those results support the overall positive impression of sawyers about visual aspects of wood pieces sawn in real industrial conditions just after the opening of the enclosure. However, these results cannot be generalized to other species such as Beech (Moreau and Barré, 2010). The adherent bark makes the darker colouration confined to the surrounding wood, with few impacts on sawing patterns. Nevertheless, it would be insightful to investigate whether this coloration is potentially problematic for paper industry.

Regarding those results, one may wonder if this process could be considered as a real alternative to wet storage. By comparison, wet storage makes logs more fresh (Syme and Saucier, 1995) but also heavier to transport from terminals to industrial sites. However, the increase of permeability due to wet storage allows reducing the drying delays (Schmulsky, 2002). On the contrary, sprinkling storage often causes discolouration on the pit membranes of wood cells, which may have a negative effect on the final product quality (Hildén et al., 2006). Regarding mechanical properties, Liese (1984) reported reductions for Spruce logs up to 10 to 35 % in dynamic bending strength after three years of wet storage.

However, in general, modulus of elasticity and modulus of rupture of wet-stored logs always satisfy the standards requirements for construction timber (Moltesen et al., 1974, Syme and Saucier, 1995).

From an operational angle, costs are main drawbacks for using anaerobic storage. Despite low operating and maintenance fees, the whole storage process is more expensive than sprinkling storage, due to higher unit labour costs and installation expenses (Richter and Richter, 2003). The minimal storage duration required to balance sprinkling storage costs is estimated around 36 months (Riguelle et al., 2010). Furthermore, anaerobic storage in sealed enclosures does not allow storing huge amount of wood by unit of surface. Sprinkling storage remains in this context the best option for maximizing profitability. Anaerobic storage is also less flexible for industry because timber cannot be destocked on demand.

Anaerobic storage appears more complex probably because of its novelty, but as for sprinkling storage, operators have to be trained regularly. Both methods request site preparation and have their own requirements, but anaerobic storage can be done on a larger range of conditions, for instance with no access to water or electricity. Furthermore, the limited impact on the environment could be an argument in favour of anaerobic storage, even more in a continuously constringent context in regards to environmental impacts of industrial activities. In a complex decisional context, even straightened after a storm, this kind of study on wood quality associated to anaerobic storage could help stakeholders to balance advantages and disadvantages and choose optimal solution to store wood for long periods.

GENERAL DISCUSSION

This thesis addressed in an original way the storm damage risk, the major abiotic threat for Belgian and Western-Europe forests, focusing on risk analysis and decision-making processes. As highlighted in our review paper (Riguelle et al., 2016a), storm damage management is a multifaceted and complex issue, calling for advanced risk analysis. The best way to deal with complexity and uncertainty throughout the risk analysis process is therefore to change the perspective and adopt an integrated approach of storm damage risk, which should be part of a wider forest risk governance framework.

However, integrated approaches are embracing a lot of information and their implementation could be difficult. According to that, we suggest a systemic approach to deal with storm damage issues. We assume that a crisis management strategy will not be optimal if some individuals are suffering from crisis conditions within the system. In contrast, we believe a balanced solution for the whole sector will likely benefit all stakeholders individually. The resulting idea is to evaluate all possible mitigation scenarios through a systemic prism, with the help of appropriate decision support systems. This approach requests, however, to characterize the system at stake (activity, scope, internal and external drivers) in order to define the targeted equilibrium state.

According to this hypothesis, a main objective of this thesis was to develop a modelling tool applied to regional forest-based sector (the *system*) for managing windthrow crises and supporting decisions with a systemic perspective. Our main requirements were to produce reliable management scenarios, without introducing too much parameters or generating uncertainty. Therefore, the model was developed step by step, together with stakeholders. Due to this participative process, the *WALFORM* model and the model-based decision-support system *WIND-STORM* (Riguelle et al., 2015a) reached a good level of prediction while staying accessible for final users. Another added-value of the model is to foster preparedness before the next hazard. Indeed, the DSS should be used to identify and remove bottlenecks within the system before the next huge storms.

Main limitations of this tool are from our point of view fourfold. First, the complete validation of the DSS was not done in real crisis conditions, because Wallonia did not experience huge storms since 1990. It means that some hypothesis are either based on past experience from 1990 or formulated in a very theoretical way, which could have caused biases in the modelling process. Second, the quality and effectiveness of decisions are conditioned to a collegial decision-making process. If decision-makers fail to hear different opinions, the result will be biased. In addition, there is still a reluctance of public decision-makers in Wallonia to use modelling tools for policy or strategic purposes. This lack of confidence is fed by the fact that the DSS cannot provide them the optimal solution, but only a set of possible solutions. Finally, we have to highlight the progressive lack of monitoring, especially in data management, when the tool was transferred from the Research to the administrative field.

We also believe in the development of contingency plans which could clearly contribute to enhance preparedness and response towards unexpected storm events. However, this concept is emerging in forestry and often results from crises, not from a continuous and proactive planning process. We observed that implementing this approach might be difficult in the forest sector, which is not familiar with those somewhat abstract concepts. Furthermore, because there is no damaging event for assessing its performance, there is still some reluctance from the end-users to involve in its daily improvement and maintenance. This is probably the main danger of developing contingency plans: if they are only used as umbrellas by decision-makers, they certainly won't be effective.

We have also chosen to address the operational level of management in this thesis. Through the timber storage case, we've demonstrated that a good strategy can fail when operational issues are not addressed. Timber storage in Wallonia is a good illustration of this lack of preparedness. Most of time, previous timber storage terminals have been abandoned and progressively used for other purposes. As for strategic management, the loss of experienced people and of technical knowledge can be dramatic for the forest sector. Through this work, we tried to highlight that strategic, tactical and operational aspects of timber storage should be considered together in order to define a flexible regional strategy for wood conservation. In this context, identifying a network of potential sprinkling storage terminals is a first step that should be extended by enhancing a real collaboration between public and private stakeholders on this topic. Furthermore, we also demonstrated that a flexible storage policy should consider a mix of conservation methods according to the quality of stored products and the industrial goals. Anaerobic storage could be one of them, according to our comforting results about its impact on spruce mechanical and physical properties.

Moreover, we can't conclude without pointing the human factor as a source of internal uncertainty and failure within the risk governance process. On the one hand, the loss of experienced people (retirement, etc.) within organisations can threaten or slow down the implementation of crisis management measures. It is thus crucial to train new workers and disseminate the knowledge. On the other hand, risk perception and acceptability of people involved in the process – decision-holders as well as operating staff – can make the strategy ineffective. For example, people who already experienced a huge storm don't react in the same way than others. This empirical knowledge can be useful for assessing and managing the risk, nevertheless, it can also be misleading if the context has drastically change since this event. We must also point out that political or personal agendas may endanger the establishment of a common strategy.

Regarding this latest concern, it is insightful to mention the specific work we've done with stakeholders in Belgium, especially in Wallonia. During seven years, we worked for and together with regional stakeholders to ensure that our scientific outputs matched with operational and sectoral expectations and requirements. The following examples, which can be seen quite disconnected from a pure scientific work, illustrate this substantial added-value of this work:

- Set up of a contingency plan
- Organization and animation of specific trainings for public bodies
- Dissemination of technical knowledge through the publication of several articles
- Development of an on-line application for storm damage data recording
- Teaching students and stakeholders regarding forest risks
- Organization of study days and field trips about timber storage management

To conclude, it is useful to highlight key challenges that should be tackled in the upcoming years. First, we would like to recall some recommendations to forest decision-makers in Wallonia, on the basis of those drawn in section 3.4.

Adopt a forest risks governance approach and define a strategy for dealing with abiotic and abiotic risks at the regional level. For example, no one can presently say what the main lines of regional strategy will be for the next crisis.

Make public decision-makers aware and consistent regarding risk management. We frequently faced high level officials who were not aware of risk management issues in their own business. In addition, they often consider contingency plans as umbrellas.

Enhance the economic resilience of the forest-based sector by i.e. supporting local industries, ease access to public financial support, and adopt a long-term forest policy to secure investments (confer the risk governance approach). As an illustration, the present uncertainty about softwood timber supply at mid and long-term may cause the relocation of facilities or underinvestment.

Facilitate the implementation of decisions both in administrative and political arenas, since current procedures do not enable fast support in the aftermath of storms. Decision-holders should adopt more flexible decision-making processes, simplify internal procedures, and enhance the development of IT-solutions.

Regarding the European forest sector, we would also like to emphasize global challenges for the forest community in the future. At the local level, a key element is from our point of view gathering and diffusing information about forest risk management issues. For example, there is a crucial need to transfer research results, which are numerous, from the Research community to forest managers and forest-based industries in simple and comprehensive ways. Research community should also vulgarize and make decision-support tools and methodologies accessible to end-users, and explain how it can be used within the decisional processes. In addition, the research community should also carry on assessments of stakeholders' perception of risk, especially regarding climate change. As highlighted by Blennow and Persson (2009), the strength of belief in climate change is a crucial factor explaining differences in adaptation strategies by forest owners and professionals. This type of assessment (e.g. Blennow, 2012, Yousefpour et al., 2013, van Gameren and Zaccai, 2015, Yousefpour and Hanewinkel, 2015) definitively helps calibrating public policies in regards to the stakeholders' perception of climate-induced risks in forestry (Keenan, 2015).

The economic context, however, remains the main driver of forest investment and management decisions. Whereas regional public authorities have few levers in a globalized world, they can act locally to foster the resilience of the forest-based sector towards crises, for instance by designing more flexible regulations, limiting administrative constraints, securing forest investments or promoting the use of local products. In fact, the higher the confidence on the system is, the better the sector will face huge disturbances as storms. Furthermore, it is also important to explore risk perception from forest-based industries angle, in order to develop fully integrated risk management policies, encompassing industry needs and aims (Hartebrodt and Chtioui, 2016).

At the supra-regional level, the main challenge is indubitably to enhance collaboration between stakeholders and decision-makers, both public and private. The set of recommendations provided to the European Commission by Gardiner et al. (2010) should be implemented to support Members States in understanding and managing storm risk. The most relevant initiative is probably the development of an European Forest Risk Facility (FRISK-GO project, Schuck et al., 2013, Landmann et al., 2015) to enhance cooperation and knowledge transfer between Members States within this platform. In addition, because forests storm damage is threatening the emerging multi-functionality goals assigned to European forests, it implies mobilizing knowledge outside the forestry sector, and integrating local experts' views and stakeholders' expectations in the decision-making process (Spathelf et al., 2014). In our opinion, storm damage management is really an open topic, about which forest community should learn continuously from other disciplines, especially social sciences and economics (see e.g. Gollier and Treich, 2003).

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Appendix

Table 13. Description of stocks, flows, and converters (variables and constants) of the WALFORM model (sorted alphabetically). Column AGG indicates if data are aggregated (+), specified by group of species (G), or by type of species (T).

Name	Description	Unit	AGG
STOCKS (13)			
ASSIM HARDW	Amount of hardwood (regional + import) processed by industries	m^3	T
ASSIM SOFTW	Amount of softwood (regional + import) processed by industries	m^3	T
PRIOR TIMB	Amount of timber sold before the storm and not yet harvested	m^3	G
ROUNDWOOD	Amount of roundwood transported to industries	m^3	G
STORAGE	Amount of windfalls on storage terminals	m^3	G
TIMB HARV	Amount of timber to harvest (timber sold)	m^3	G
TIMB SALE	Amount of timber on sale	m^3	G
TIMB TRANSP	Amount of timber to transport (harvested) out of forests	m^3	G
TRANSF HARDW	Amount of regional hardwood in industries	m^3	T
TRANSF SOFTW	Amount of regional softwood in industries	m^3	T
WIND HARV	Amount of windfalls to harvest (windfalls sold + exchanged)	m^3	G
WIND SALE	Amount of windfalls on sale	m^3	G
WIND TRANSP	Amount of windfalls to transport (harvested) out of forests	m^3	G
FLOWS (18)			
Exp hardw	Export capacity (hardwood)	m^3/month	T
Exp softw	Export capacity (softwood)	m^3/month	T
Hardw	Amount of regional hardwood arriving to industries	m^3/month	T
Hc prior	Harvesting capacity (prior timber)	m^3/month	G
Hc timb	Harvesting capacity (timber)	m^3/month	G
Hc wind	Harvesting capacity (windfalls)	m^3/month	G
Ic hardw	Industrial capacity (hardwood)	m^3/month	T
Ic softw	Industrial capacity (softwood)	m^3/month	T
Imp hardw	Import capacity (hardwood)	m^3/month	T
Imp softw	Import capacity (softwood)	m^3/month	T
In timb	Amount of timber put on the market	m^3/month	G
Pc timb	Purchase capacity (timber)	m^3/month	G
Pc wind	Purchase capacity (windfalls)	m^3/month	G
Softw	Amount of regional softwood arriving to industries	m^3/month	T
Tc destock	Transport capacity of windfalls (terminals to industries)	m^3/month	G
Tc stock	Transport capacity of windfalls (forests to terminals)	m^3/month	G
Tc timb	Transport capacity of timber (forests to industries)	m^3/month	G
Tc wind	Transport capacity of windfalls (forests to industries)	m^3/month	G

Name	Description	Unit	AGG
CONVERTERS (61)			
dam mob	Share of storm damage put on the market	%	+
damage	Amount of storm damage (assessed at the regional level)	m^3	+
delay pay	Activation of payment delays (Yes or No)	-	+
demand	Variation in market demand for regional resources (per year)	%	G
diff harv	Differential of harvesting productivity in wind-damaged areas	%	+
diff imp	Differential of importation (positive or negative, per year)	%	T
dist store	Mean distance of transport for storage	km	+
ex hardw	Hardwood exported per month	m^3	T
ex prior hardw	Priority to hardwood export during crisis (Yes or No)	-	T
ex prior softw	Priority to softwood export during crisis (Yes or No)	-	T
ex soft	Softwood exported per month	m^3	T
exch rate	Exchange rate between windfalls and timber	%	+
fuel cap	Industrial demand for fuel wood	m^3	T
h work	Hours worked per year per truck driver	h	+
harv delay	Harvesting delays (for timber sold before the storm)	month	+
harv rate	Share of timber sold before the storm already harvested	%	+
harv syst	Harvesting systems (share between manual, mechanized and mixed)	%	+
harvesters	Number of harvesters available	-	+
hc inaccess	Mean inaccessibility of forest roads (month of the year)	%	+
hc ratio wind	Share of harvesting capacity dedicated to windfalls	%	+
hc share wind	Share of harvesting capacity by type of species (windfalls)	%	G
hc tot	Maximal harvesting capacity	m^3/month	+
hc tot timb	Maximal harvesting capacity for timber	m^3/month	+
im hardw	Level of importation (hardwood)	m^3/month	T
im softw	Level of importation (softwood)	m^3/month	T
load unload	Time for loading and unloading trucks	h	+
man prod	Productivity of manual harvesting system (per workers)	m^3	+
mean density	Average density of wood loading	t/m^3	+
mean dist	Mean distance of transport from forests to industries	km	+
mean speed	Average truck speed	km/h	+
mec prod	Productivity of mechanized harvesting system (per harvester)	m^3	+
mma	Maximum mass authorized for trucks	t	+
nb trucks	Total number of trucks available	-	+
offer	Share of usual timber supply sold (positive or negative, per year)	%	G
panel cap	Industrial demand for panelling	m^3	T
pay delay	Payment delays (for timber sold before the storm)	%.month	+
pc ratio wind	Share of purchase capacity dedicated to windfalls	%	+

Name	Description	Unit	AGG
pc share wind	Share of purchase capacity by type of species (windfalls)	%	G
pc tot	Maximal purchase capacity	m^3/month	+
price init	Mean stumpage prices before the storm	€/m^3	G
pulp cap	Industrial demand of pulpwood	m^3	T
red prod	Industrial productivity variation (positive or negative)	%	+
saw cap	Industrial demand for sawing	m^3	T
skidders	Number of harvesters available	-	+
stock	Amount to store (maximal value)	m^3	G
tare weight	Weight of the truck without loading	t	+
tc inaccess	Inaccessibility of forest roads (per month of the year)	%	+
tc ratio wind	Share of transport capacity dedicated to windfalls	%	+
tc share wind	Share of purchase capacity by type of species (windfalls)	%	G
timb dev	Devaluation of timber stumpage prices due to the storm	%	G
timb price	Timber stumpage prices after the storm	€/m^3	G
timb to pay	Amount of money to pay for timber sold before the storm	€	+
tr fact	Truck productivity factor	m^3/km.t.truck	+
trucks rep	Share of transport capacity dedicated to storage operations	%	+
trucks wind	Number of trucks dedicated to windfalls transportation	-	+
vol timb init	Amount of timber sold before the storm	m^3	G
vol timb norm	Average amount of timber sold per year	m^3	G
wind dev	Devaluation of windfalls stumpage prices (first year)	%	G
wind dev supp	Devaluation of windfalls stumpage prices (after one year)	%	G
wind price	Windfalls mean stumpage prices	€/m^3	G
workforce	Number of fellers available	-	+

Table 14. Equations used in the WALFORM model.

For t = 0 (initial value)

STOCKS (t)

WIND SALE = damage *x* dam mob
TIMB SALE = 0
WIND HARV = vol timb init *x* (1 − harv rate) *x* exch rate
TIMB HARV = 0
PRIOR TIMB = vol timb init *x* (1 − harv rate) *x* (1 − exch rate)
WIND TRANSP = 0
TIMB TRANSP = 0
ROUNDWOOD = vol timb init *x* harv rate
STORAGE = 0
TRANSF HARDW = 0
TRANSF SOFTW = 0
ASSIM HARDW = 0
ASSIM SOFTW = 0

For t = 1 to 60 and *dt* = 1

STOCKS (t)

WIND SALE (t) = WIND SALE (t − 1) − Pc wind (t − 1)
TIMB SALE (t) = TIMB SALE (t − 1) + In timb (t − 1) − Pc timb (t − 1)
WIND HARV (t) = WIND HARV (t − 1) + Pc wind (t − 1) − Hc wind (t − 1)
TIMB HARV (t) = TIMB HARV (t − 1) + Pc timb (t − 1) − Hc timb (t − 1)
PRIOR TIMB (t) = PRIOR TIMB (t − 1) − Hc prior (t − 1)
WIND TRANSP (t) = WIND TRANSP (t − 1) + Hc wind (t − 1) − Tc wind (t − 1) − Tc stock (t − 1)
TIMB TRANSP (t) = TIMB TRANSP (t − 1) + Hc prior (t − 1) + Hc timb (t − 1) − Tc timb (t − 1)
ROUNDWOOD (t) = ROUNDWOOD (t − 1) + Tc timb (t − 1) + Tc wind (t − 1) + Tc destock (t − 1) − Exp hardw (t − 1) − Exp softw (t − 1) − Hardw (t − 1) − Softw (t − 1)
STORAGE (t) = STORAGE (t − 1) + Tc stock (t − 1) − Tc destock (t − 1)
TRANSF HARDW (t) = TRANSF HARDW (t − 1) + Hardw (t − 1) − Ic hardw (t − 1)
TRANSF SOFTW (t) = TRANSF SOFTW (t − 1) + Softw (t − 1) − Ic softw (t − 1)
ASSIM HARDW (t) = ASSIM HARDW (t − 1) + Ic Hardw (t − 1) + Imp hardw (t − 1)
ASSIM SOFTW (t) = ASSIM SOFTW (t − 1) + Ic softw (t − 1) − Imp softw (t − 1)

FLOWS (t)

Pc wind (t) = MIN [(((pc tot (t) /wind price (t)) *x* pc ratio wind) − Pc wind (t − 1)), WIND SALE (t)]
Pc timb (t) = MIN [(((pc tot (t)/timb price) *x* (1 − pc ratio wind)) − Pc timb (t − 1)), TIMB SALE (t)]
In timb (t) = offer (t) *x* vol timb norm (t) *x* timb rep (t)
Hc wind (t) = MIN [(hc tot (t) *x* diff harv *x* hc ratio wind), WIND HARV (t)]
Hc prior (t) = MIN [hc tot timb (t), PRIOR TIMB (t)]

Hc timb (t) = MIN [(hc tot timb (t) − Hc prior (t)), TIMB HARV (t)]

Tc timb (t) = MIN [(nb trucks *x* mma *x* tr factor *x* (1 − tc ratio wind) *x* (1/mean dist) *x* (1 − tc inaccess)), TIMB TRANSP (t)]

Tc wind (t) = MIN [(trucks wind *x* trucks rep *x* mma *x* tr factor *x* (1/ mean dist) *x* (1 − tc inaccess)), (WIND TRANSP (t) − tc stock (t))]

Tc stock (t) = MIN [(trucks wind *x* trucks rep *x* mma *x* tr factor *x* (1/dist store) *x* (1 − tc inaccess)), WIND TRANSP (t), (stock − STORAGE (t − 1))]

Tc destock (t) = MIN [(trucks wind *x* trucks rep *x* mma *x* tr factor *x* (1/dist store) *x* (1 − tc inaccess)), STORAGE (t)]

Exp hardw (t) = MIN [ex hardw (t), ((ROUNDWOOD (t) − Exp softw (t) − Softw (t)) – Hardw (t))]

Exp softw (t) = MIN [ex softw (t), ((ROUNDWOOD (t) − Exp hardw (t) − Hardw (t)) – Softw (t))]

FLOWS (t)

Hardw (t) = MIN [Ic hardw (t), (ROUNDWOOD (t) − Softw (t) − Exp hardw (t) – Exp softw (t))]

Softw (t) = MIN [Ic softw (t), (ROUNDWOOD (t) − Hardw (t) − Exp hardw (t) – Exp softw (t))]

Ic hardw (t) = MIN [((pulp cap + saw cap + panel cap + fuel cap) *x* (1 − diff imp) *x* red prod), TRANSF HARDW (t)]

Ic softw (t) = MIN [((pulp cap + saw cap + panel cap + fuel cap) *x* (1 − diff imp) *x* red prod), TRANSF SOFTW (t)]

Imp hardw (t) = im hardw (t) *x* diff imp (t)

Imp softw (t) = im softw (t) *x* diff imp (t)

CONVERTERS (t)

wind price (t) = price init *x* (wind dev (t) + wind dev supp (t))

timb price = price init *x* timb dev

timb to pay = (vol timb init *x* price init) *x* (1 − pay delay)

pc tot (t) = (vol timb norm *x* timb price *x* (1+diff imp) *x* (1+demand)) − timb to pay

hc tot (t) = ((man prod *x* workforce) + (mec prod *x* harvesters)) *x* harv syst *x* (1 − hc inaccess))

hc tot timb (t) = hc tot (t) *x* (1 − hc ratio wind)

tr factor = (h work/(((mean dist/mean speed) *x* 2) + load unload)) *x* ((mma − tare weight)/mean density)

trucks wind = nb trucks *x* tc ratio wind