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Fuzzy Design Science Research

Edy Portmann, Gwen Wilke, Luis Téran and Sara D'Onofrio.





Lotfi A. Zadeh

This booklet is dedicated to Lotfi Zadeh, the visionary behind fuzzy design science research. In 1965, he authored his seminal paper on fuzzy sets. This landmark paper initiated a new direction which, over the past decades, has led to a vast literature and a rapidly growing number of applications. In the future, the impact of fuzzy sets, logic and systems is likely to be felt evermore not only in the realm of academia, but also in business, government, and society.

Message from the Founder



With today's information overload, it has become increasingly difficult to analyze the huge amounts of data and to generate appropriate management decisions. Furthermore, the data are often imprecise and will include both quantitative and qualitative elements. For these reasons it is important to extend traditional decision-making processes by adding intuitive reasoning, human subjectivity, and imprecision. To deal with uncertainty, vagueness, and imprecision, Lotfi Zadeh introduced fuzzy sets, logic and systems.

At the FMsquare Foundation, for instance, fuzzy logic is applied to extend portfolio analysis, scoring methods, customer relationship management, performance measurement, web reputation, web analytics and controlling, community marketing, and other business domains to improve managerial decisions and much more. Thus, we see fuzzy sets, logic and systems as an innovative management method where appropriate concepts, software tools and languages build a powerful instrument for analyzing and controlling business, government, and society.

Andreas Meier, Founder



Welcome

Message from the Presidents



With fuzzy design science research, we create ethical and sustainable innovations for business, governance and society. Following our research framework, FMsquare conceptualizes and tests research approaches to ethical and sustainable artificial and, as a nature-inspired subset, computational intelligence by exploiting fuzzy management methods:

- We enable our researchers to experience and tackle real-world problems in the context of ethical and sustainable design of computational intelligence technologies through collaborative and reflective interaction.

- We give the researchers freedom and responsibility to explore and experience interactive ways of doing methodologically sound design science research.
- We support and develop research projects by providing conceptual input, tools and critical reflection on how to run inter- and transdisciplinary collaboration in trustworthy artificial intelligence research.
- We integrate knowledge and values from different scientific perspectives, as well as from other societal actors. We propose key expertise in problem framing and knowledge integration.
- We seek to strengthen intra- and cross-disciplinary teaching collaboration and build bridges within academia, business, government and society.

Edy Portmann, President

Gwen Wilke, Vice President

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Our formula to invent a sustainable future is a research environment that encourages researchers to ask questions that no one else has thought to ask.

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The Incompatibility Principle

A new lens for scientific inquiry



Science seeks to examine the world in measurable parts and confidently predict outcomes. Such thinking can be incompatible with the messiness of the real world and produce results that are mathematically elegant but practically meaningless.

As you step into the challenging and exhilarating world of graduate research, you're probably eager to apply the tools of precision and certainty that have served science so well for centuries. But what if we told you that the concepts of precision and certainty might be holding you back from truly understanding the complexity of the systems you'll study?



Meet the Principle of Incompatibility – a concept that's as revolutionary as it is unsettling. Articulated by Lotfi Zadeh, a mathematician, electrical engineer, computer scientist, artificial intelligence researcher, and the visionary behind fuzzy logic, this principle suggests something that seems unfortunate: the more complex a system, the less likely we are to make precise and meaningful statements about it. In other words, as complexity increases, our cherished tools of binary logic – those clear, yes-or-no distinctions – begin to fail us.

The paradox of precision in a complex world

Science, in its traditional form, thrives on clarity – it seeks to break down the world into measurable parts, define variables with exactitude, and predict outcomes with confidence. This approach has driven incredible advances, from the laws of motion to the wonders of modern medicine. But venturing into the realms of human behavior, ecosystems, or economic systems, the neat lines of binary logic begin to blur.

From physics we know that precise assertions are never certain. The power of a vague assertion rests in its being vague.

The Principle of Incompatibility forces us to confront an inconsistency: as we seek to understand more complex systems, tools to make sense of those more straightforward – precise definitions and exact measurements – become less effective. When dealing with the intricacies of social systems, for instance, binary classifications can fall short. Human behavior can't be neatly boxed into categories like 'rational' or 'irrational', and economic trends rarely fit into simple 'boom' or 'bust' models. Such systems are riddled with nuances and interdependencies that defy the rigid boundaries of traditional logic.

Image credit: Massoud Nikravesh

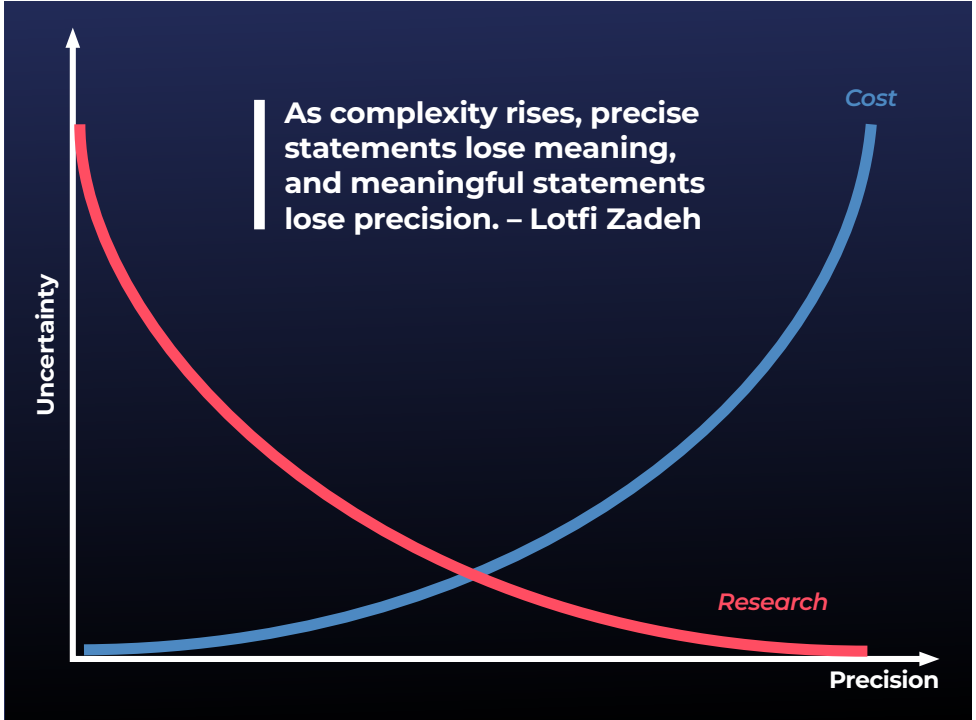


Fig.1 French physicist Pierre Duhem was the first to point out the Principle of Incompatibility. He suggested that the certainty that a proposition is true decreases with any increase of its precision. Duhem's principle is analogous to Werner Heisenberg's principle of uncertainty; precision and uncertainty are inversely proportional. Fuzzy Logic models vagueness and reflects this principle.

The Principle of Incompatibility tells us that if you try to force precise models onto a complex system, your results may be mathematically elegant but practically meaningless. This is not just a minor inconvenience; it's a fundamental challenge to how we think about science.

Fuzzy Logic: Navigating the incompatibility

So, what do we do when faced with this incompatibility? Do we throw up our hands in despair? Not quite. This is where fuzzy logic steps in, offering a way to embrace complexity rather than being defeated by it. Fuzzy logic is Zadeh's ingenious response to the limitations highlighted by the Principle of Incompatibility.

It abandons the rigid binary of true/false, yes/no, and introduces the concept of partial truth. In fuzzy logic, a statement can be 'somewhat true', 'mostly false', or anywhere between. This might sound like a weakening of the scientific method, but it's a powerful tool for navigating the messy, real-world systems that defy simple categorization.

Take, for instance, the challenge of modeling human emotions. Traditional logic would force us to label an emotion 'happy' or 'not happy'. But anyone who's ever felt a complex mix of emotions knows that this binary categorization doesn't capture the reality of human experience. Fuzzy logic allows us to describe emo-

tions with degrees of truth – someone can be ‘60% happy’, acknowledging that they might also be experiencing sadness, anxiety, or contentment simultaneously.

But fuzzy logic isn’t just about more realistic descriptions; it’s about better decisions. In fields like medicine, fuzzy logic can improve diagnostic systems by allowing for uncertainty and overlapping symptoms. Rather than forcing a diagnosis into a rigid category, fuzzy logic lets the system express varying degrees of likelihood, providing a more nuanced and realistic assessment to guide better treatment decisions.

Incompatibility in research: Embrace the fuzziness

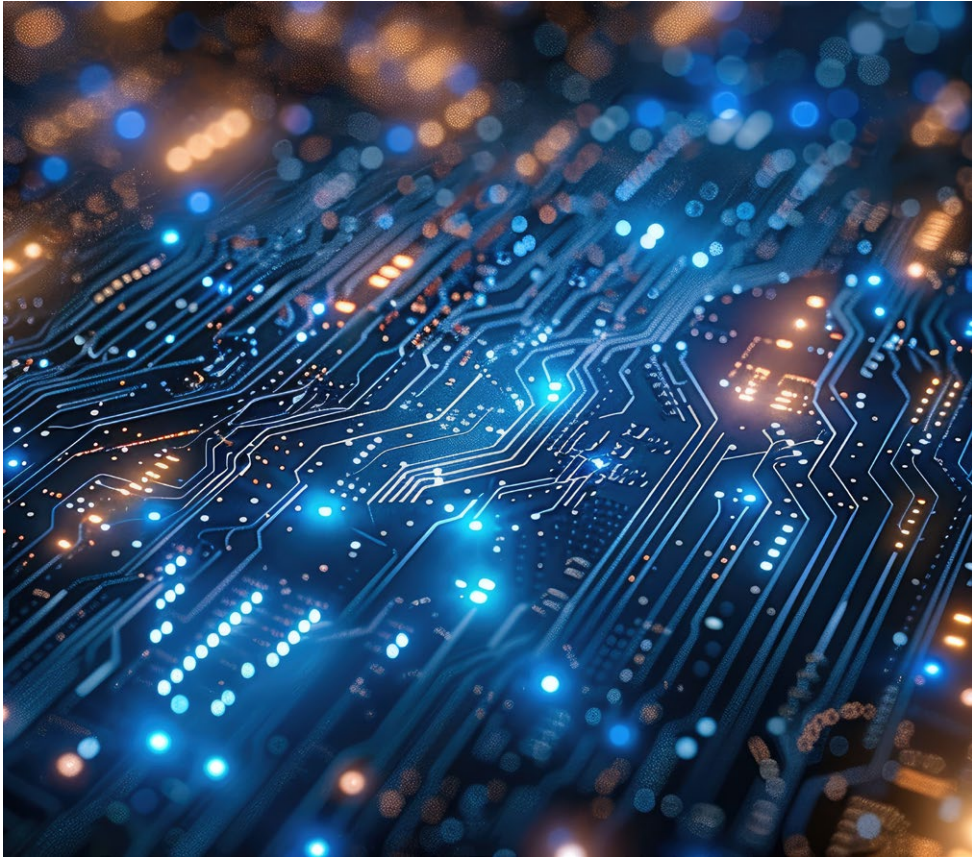
As you embark on your journey, you’ll inevitably confront the complexity and unpredictability that the Principle of Incompatibility describes. Traditional research methods will tempt you to simplify, to force precision where it doesn’t be-

long. But we urge you to resist that temptation. Instead, consider how embracing the fuzziness inherent in complex systems can lead to more meaningful insights.

Design Science Research, a field increasingly crucial in informatics and business, provides a compelling example of how to navigate this incompatibility. The goal isn’t to achieve perfect precision but to create artefacts – models, processes, or systems – that work in practice. These artefacts must account for the messiness of the real world, and fuzzy logic is a critical tool in making them functional and relevant.

When you design a system with fuzzy logic, you’re not just acknowledging the complexity of the real world – you’re actively using it to your advantage. Fuzzy logic helps you build robust systems in the face of uncertainty, adaptable to changing conditions, and capable of providing insights that rigid, binary models simply cannot.





Redefining scientific rigor

The Principle of Incompatibility and fuzzy logic challenge the traditional view of scientific rigour. They suggest that the pursuit of absolute precision may sometimes lead us astray, especially when dealing with the complex, interconnected systems that dominate today's scientific landscape. Instead, they propose a new kind of rigor – one that eschews the limits of binary thinking and embraces the complexity and ambiguity of the real world.

As you progress in your research, we encourage you to rethink what it means to be precise and rigorous. Don't shy away from the fuzziness of

your data or the ambiguity of your models. Instead, use fuzzy logic to turn these challenges into opportunities. By doing so, you'll be better equipped to tackle the complexities of your research and to generate insights that are not only accurate but also profoundly meaningful.

Welcome to a new way of thinking about science – where incompatibility isn't a roadblock but a gateway to deeper understanding. Through the lens of fuzzy logic, you'll discover that the most profound insights often lie in the gray areas, where precision meets possibility, and the complexity of the real world can finally be understood on its own terms.

Personal response

Enric Trillas is a mathematician devoted, from the first hour, to research into fuzzy logic. We asked him about his views on the further development of this research area.

Any linguistic description of any aspect of reality or any (interesting) conversation either with oneself or with another person will always be full of imprecise words. This is stated in Lotfi Zadeh's *Incompatibility Principle* (1973). Try to debate anything without using a single imprecise word – you will observe that this is very difficult and makes one appear an extremely fussy person.

Let's look at common sense reasoning as a specialization of thought directed to reach some goal that, closely interwoven with our ordinary languages, frequently just concludes a conjecture that, if sometimes allows to finally reach either consequences, or hypotheses, or refutations, many times just allows speculations, nevertheless the root of creativity. Reasoning not only consists in deducing, abducting, and refuting, but also in inducing.

If we analyse common sense reasonings by means of mathematical calculations, with formulas representing statements, it can help us better understand the 'structure' embedded within it – a process comparable to scientists studying natural phenomena. Therefore, viewing reasoning and language as what they really are, natural phenomena, helps us to speculate on an approach to both through a new theoretical and experimental science, that is, by means

of something like a 'Physics of Language and Reasoning'.

Gottfried Leibniz, a philosopher, mathematician and lawyer in the 17th century, dreamed of a machine that could calculate ideas, enabling him to study law and morals as systematically as other natural sciences and, as a result, resolve legal disputes with as much precision as a mathematician performing calculations. His dream was shortened in his famous statement: 'Not discuss, let's calculate!'

There have been efforts in the past: in 1847, George Boole developed Boolean algebra, which laid the groundwork of binary logic – that linked with precision – but was unable to capture nuances of human language like its intrinsic imprecision or vagueness.

However, now we might see Leibniz' dream become a reality. In his 2012 book *Computing with Words*¹, Zadeh demonstrates how to express complex statements using formulas and functions. Today, we also see the development of Generative Artificial Intelligence making us believe in the immediacy of machines 'thinking' like human beings, but without using neither a Natural Language, nor reaching speculations with which it can independently obtain something new and relevant.

In any case, and in my view, to pave the ground supporting machines exhibiting a true thought, to think like people, it is imperative to continue Lotfi Zadeh's work!



Photo credit: Andrés Trillas

Biography:

Enric Trillas is a retired professor of Computer Science and Artificial Intelligence who first taught at the Technical University of Catalonia and then at the Technical University of Madrid. Between 1983 and 1996, Trillas held several positions related to Science and Technology in the Spanish Government. With more than 400 papers and fifteen books, he was awarded medals, prizes, 'Honoris Causa' degrees, and was an Emeritus Researcher for the defunct 'European Centre for Soft Computing'.

¹ Lotfi A. Zadeh (2012): *Computing with Words*. Springer Berlin, Heidelberg. link.springer.com/book/10.1007/978-3-642-27473-2

Design Science Research

Enhancing our understanding of the systems we create

Where business and technology intersect, information systems are increasingly critical; understanding their rapid evolution demands a deep respect for their complexity.

Information systems (IS) are the backbone of modern organizations, driving everything from data management to decision-making, increasingly so where business and technology intersect and where innovation is both the currency and the fuel. To keep pace with technological advances and the growing complexity of business needs, a robust and flexible approach to problem solving is essential. This is where Design Science Research (DSR) comes into play – a methodology that not only solves pressing problems but also enhances our understanding of the systems we create. In its application, DSR

can extend far beyond the realms of modern organizations.

DSR is a unique approach that emphasizes the creation of innovative artefacts – practical solutions such as software tools, frameworks, and methods specifically designed to address challenges within information systems. But DSR is not merely about creating functional tools; it's about understanding the 'why' behind their effectiveness.

It is this 'why' that is why, in the realm of IS, where the integration of technology and business processes is crucial, DSR plays a pivotal role. It allows researchers and practitioners to develop artefacts that are not only innovative



but also deeply informed by a rigorous evaluation process. This dual focus on creation and understanding makes DSR a powerful tool for advancing both the practical and theoretical aspects of information systems.

An iterative process

The DSR process is systematic and iterative, beginning with identifying a problem or a gap within an information system. This could be anything from the need for better data security protocols to the development of more user-friendly interfaces for enterprise software. Once the problem is defined, researchers design an artefact addressing this issue.

However, the creation of the artefact is just the beginning. In information systems, where

the real-world application is the ultimate test, the artefact must undergo rigorous evaluation. This involves deploying the artefact in a practical setting – such as within a company's IT infrastructure – and assessing its performance. Does it enhance system efficiency? Does it mitigate identified risks? These questions guide the evaluation process.

The insights gained from this evaluation are invaluable. They not only inform refinements to the artefact itself but also contribute to the broader body of design knowledge. This knowledge is essential for understanding the principles that govern successful information systems, providing a foundation for future innovations.

Real-world applications

One of the most significant contributions of DSR to information systems is its ability to produce actionable knowledge that directly improves IS practices. For example, consider the challenge of managing large-scale data in an organization. Traditional approaches might focus on optimizing existing systems, but through DSR, researchers could develop a novel data management tool that not only handles large volumes of data more efficiently but also integrates advanced analytics to provide real-time insights.

What we design will in turn design us back. Hence we must innovate mindful systems that affect us positively.

Through the DSR process, this tool would be rigorously tested within the organization, allowing researchers to refine its features based on real-world feedback. The resulting artefact would not only solve the initial problem but also contribute to design knowledge about effective data management practices in complex IS environments.

IS Research

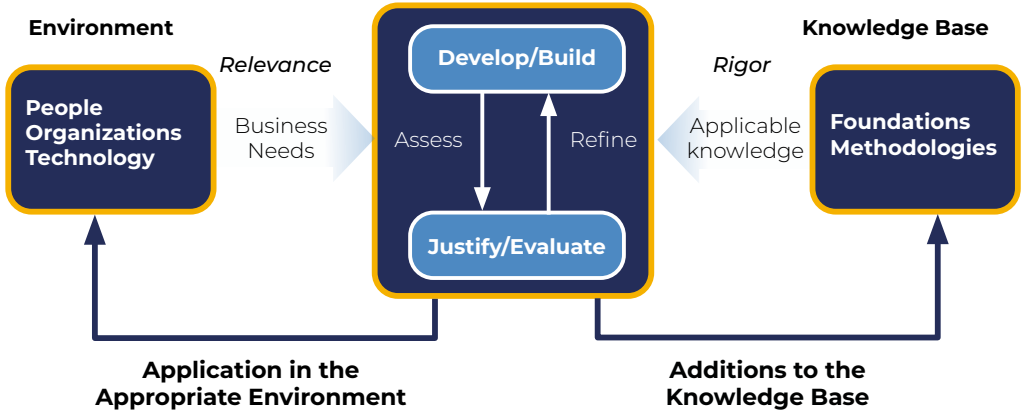


Image credit: Alan Hevner et al.

Fig. 2 Design Science Research comprises a relevance cycle, which reflects the requirements by analysing business needs within the environment; a rigor cycle, which ensures grounding of research in foundations, methodologies and theories, while adding new knowledge to a knowledge base (which informs the design process of the planned artifact); and a design cycle, which highlights design, development and evaluation of the artifact.

Such advancements are not confined to specific challenges. Whether improving user interfaces, enhancing cybersecurity measures, or stream-

lining business processes, DSR provides a structured yet flexible framework for driving innovation in information systems.



The broader implications

While DSR is most applied within information systems, its principles have broader implications. The methodology’s focus on creating practical, effective solutions through iterative refinement can be applied to various domains, including those outside traditional business environments.

Design is the science of the artificial.

One of the most intriguing aspects of DSR is its potential to influence how we approach problem solving in our daily lives. The same principles that drive innovation in IS – efficiency, continuous improvement, and practical application – can be harnessed to create tools and systems that enhance personal productivity, health management, and even our relationships.

Imagine applying DSR to develop a personal finance app that not only helps users budget more effectively but also adapts to their spending habits over time, offering personalized advice and insights. This application illustrates how the precision and innovation of business practices can be translated into tools that improve everyday life.

In the end, DSR is more than just a methodology – it's a way of thinking, a way of bridging the gaps between the abstract and the concrete, between theory and practice, and between business and life. And as we continue to explore its potential, we may find that it's not just building bridges but entire worlds of possibility.

Personal response

In your opinion, what are the basics of a Design Science Research project?

Design Science Research (DSR) aims to create practical solutions to real-world issues by developing and assessing new artifacts, such as models, frameworks, or systems, that address specific challenges. A DSR project often follows an iterative cycle that includes identifying a problem in a specific domain, defining objectives, designing a solution, testing it in real or simulated settings, and evaluating its impact. This methodology bridges theory and practice, advancing both academic understanding and innovation through applicable solutions in real-world problems.

How do fuzzy models support your research project?

In DSR, fuzzy models are particularly advantageous because they can address the complexity and uncertainty common to real-world problems. Unlike traditional models that rely on binary outcomes, fuzzy models accommodate varying degrees of truth, offering more nuanced and detailed

insights. During the design and evaluation stages of DSR, fuzzy models are invaluable for capturing stakeholder input, quantifying uncertain variables, and simulating complex scenarios. This flexibility enables a data-driven exploration of solutions that can be refined iteratively.

As a proven expert in fuzzy cognitive maps, what do you think they have to do with this kind of research?

Fuzzy cognitive maps (FCMs) are a specialized type of fuzzy model used to represent concepts and their causal relationships within complex systems. FCMs are particularly valuable in DSR as they provide a visual and analytical framework for understanding how different factors interact. Each concept is represented as a node, while the connections between nodes illustrate the strength and direction of influence. This allows researchers and stakeholders to anticipate how changes in one part of the system might affect the whole. As a result, FCMs serve as a powerful tool for mapping, analyzing, and optimizing solutions in DSR projects.



Biography:

Elpiniki I. Papageorgiou is a Professor in Artificial Intelligence at the Energy Systems Department, University of Thessaly, Larissa, Greece. She specializes in developing and applying artificial intelligent models and algorithms to decision support problems for modeling, prediction, strategic decisions, scenario analysis and data mining, solving important emerging problems, arising in engineering, energy, business, medicine, agriculture and environment.

Demo-driven innovation

Applying fuzzy logic to research exploration

To prepare for an expedition into the unknown, researchers need a clear path and a state of mind that, in many respects, challenges academic conventions; fuzzy logic can help.

It's tempting to imagine that research is the search for truth – that, ultimately, something is or isn't. But Design Science Research (DSR), at its core, is an expedition into the uncharted complexities of the unknown. Lotfi Zadeh once said, 'In dealing with complex phenomena, we often use the Principle of Incompatibility: As complexity rises, precise statements lose meaning, and meaningful statements lose precision.' To unearth what no one else has revealed, research must involve non-linear activities: understanding a domain, finding novel ideas, making them applicable, gathering experience reports, validating them, educating peers, and eventually getting these ideas used in practice (Figure 3).

You, as graduate students, who typically have the time and energy to undertake the required extensive work, are the research engine. The most pressing challenge students face embarking on such an expedition is ensuring they are on the right track – a task compounded by academia's unique dynamics. Tasking graduate students with formulating, building, and defending a thesis distinct from others hinders collaboration, leading many to work in isolation.

Furthermore, DSR is inherently competitive, encouraging researchers to work in secrecy, withholding ideas until they are fully formed. This

With ‘demo or die’, the MIT Media Lab coined a twist on the dictum that a researcher must ‘publish or perish’.

solitary approach, however, limits the scope of research to small, niche topics and leaves researchers vulnerable to their own biases and assumptions. A more productive path lies in collaboration – not just with peers, who might be seen as competitors, but across different levels of the research ecosystem. Collaborating with those who can provide input or benefit



Image credit: Damien Newman

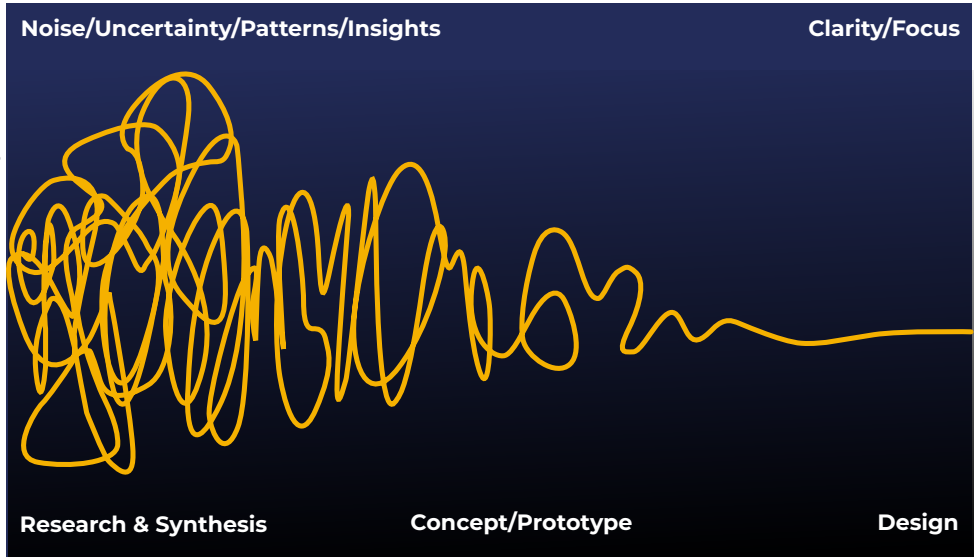


Fig. 3 The Squiggle² visualizes design science, comprising the journey of researching, uncovering insights, generating creative concepts, iteration of prototypes and eventually concluding in a solution. It encapsulates demo-driven innovation, beginning with mess and uncertainty and ending in a single point of focus.

from one’s research leads to mutually beneficial outcomes.

One effective method to combat the isolation and validate ideas is demo-driven innovation. This approach involves several critical steps designed to refine and test research artefacts in the real world.

- 1. Have a running model:** Research often revolves around models – abstract representations of reality. A DSR researcher must develop a model that solves a significant problem and is original. However, these models often remain theoretical and may not account for practical complexities.
- 2. Craft a compelling story:** Models alone can be dry. A well-crafted story can engage and excite potential collaborators and audiences, transforming complex ideas into relatable narratives.
- 3. Align story and model:** The story must accurately reflect the model. Exaggeration or mis-

representation can undermine credibility, so honesty and transparency are crucial.

- 4. Adapt model to story:** As the research progresses, the model should evolve in response to feedback and new insights, ensuring it remains relevant and understandable.
- 5. Demonstrate:** The culmination of this process is the demo – a live presentation of the model and its applications. This step requires vulnerability, as it exposes the research to scrutiny. Respecting the audience’s time by presenting a well-prepared, functional demonstration is crucial.
- 6. Listen:** The most critical aspect of a demo is listening to feedback. It can be challenging, especially if it’s negative, but this input is invaluable for refining the research.
- 7. Provide feedback:** Finally, offering constructive feedback to others fosters a collaborative environment. Engaging deeply with others’ work can provide fresh perspectives and new ideas.

²The Process of Design Squiggle by Damien Newman, thedesignsquiggle.com

This principle applies well to demo-driven innovation. As researchers delve deeper into their subjects, the complexity of their work increases. Clear, precise communication becomes challenging, but meaningful insights can emerge through the iterative process of modelling, storytelling, and demonstrating.

Demo-driven innovation, grounded in the principles of fuzzy logic, offers a structured yet flexible approach to navigating the uncertainties of Design Science Research. By continuously refining models, engaging with stories, and seeking feedback, researchers can ensure their work remains relevant, accessible, and impactful, and that their expedition into the unknown is on the right track.

Personal response

When did you develop demo-driven innovation?

It started during my PhD some 20 years ago. In particular, while I was working with Master students. They have a limited amount of time, typically a few months, for their research, and my goal was to get them to create novel research that was surprising both for them and for me.

What is the benefit of this kind of research?

Research requires exploration which requires feedback. The tighter the feedback loop, the faster we learn. The idea of 'demo or die' goes back to the 1980s and can probably be traced even further back to the work at Xerox Parc and to 'the mother of all demos', Douglas Engelbart's 1968 demonstration of experimental computer technologies that are now commonplace. But what we learnt while practicing demo-driven innovation is that the very act of repeating and refining the same story over and over, almost regardless from where we start, ends up uncovering new angles that otherwise remain hidden. The feedback comes in two ways: making the

idea executable uses the computer as a feedback source; having the story embodied in an executable model exposes it to others which offer further feedback. Now, what kind of feedback is the most interesting? Any feedback is, if you listen to it carefully. But the most interesting feedback comes in the form of new questions. There is something about making abstract ideas be tangible that makes our brain engage in new ways and form new connections.

Who is it relevant for and why?

I first used it in the context of academic software engineering research. I believe it is particularly suited to software engineering because the skills required to embody the demo are the skills required for doing the actual research. Later in my career, I used it with equal success to drive innovation in industrial settings as well. In particular, the focus on deming any aspect of the inside of a system was one of the factors that led to what today we call Moldable Development.



Biography:

Tudor Girba is a software environmentalist and CEO of feenk.com where he works with an amazing team to make the inside of systems explainable. Much of the work is embodied in Glamorous Toolkit, a novel environment that enables Moldable Development³.

³ The Glamorous Toolkit by Tudor Girba, gtoolkit.com

Fuzzy Thinking

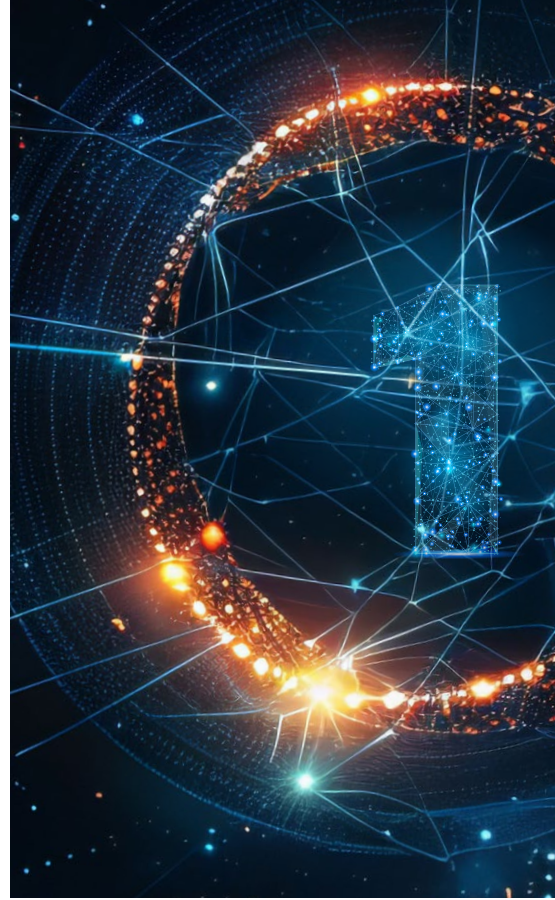
Actually, it's not that simple

To properly understand any system, you must know that what you think you know probably doesn't consider the complexities of reality.

It's time to delve a little deeper into the concept of 'fuzzy logic' and upend some of the more comfortable foundations of your thinking.

Much as we'd like to think that our avenue of work relies on clear cases of causality – if this, then that (otherwise, things wouldn't work the same way every time we flicked a switch) – paired relationships of input and output rely on complexity. The reality is that little in life – if anything – is binary, even within the verity of mathematics.

Enter Bart Kosko. An American engineer with further degrees in philosophy, mathematics, and economics, Kosko rattled conventional thinking about systems in 1993 with the release of his book 'Fuzzy Thinking'³. Unlike classical binary logic, which categorizes statements



as either true or false, fuzzy logic introduces a spectrum of truth values between 0 and 1. Uncomfortable though this may be, especially for engineers, this approach allows for a more nuanced representation of reality, where statements can partially hold truth. This is especially the case wherever humans are involved.

'Fuzzy Thinking' delves into the theoretical underpinnings of fuzzy logic and illustrates its applications across diverse fields, such as control systems and decision-making processes. The book explains how fuzzy sets, a key component of fuzzy logic, can represent complex and ambiguous information. For instance, instead of strictly categorizing temperatures as 'hot' or 'cold', fuzzy logic allows for varying degrees of 'warmness' (Figure 4).

³ Bart Kosko (1993) Fuzzy Thinking. The New Science of Fuzzy Logic. Hyperion Books. www.amazon.co.uk/Fuzzy-Thinking-New-Science-Logic/dp/078688021X



As complexity rises, precise statements lose meaning, and meaningful statements lose precision.

One of fuzzy logic's central ideas is the concept of membership functions, which define how each point in the input space is mapped to a membership value. These functions enable the modeling of partial truth; particularly useful in systems where binary logic fails to capture the complexity of human reasoning and perception.

Fuzzy logic abounds in multiple practical applications in various technologies, such as household appliances, automotive systems, and even financial markets. In fact, fuzzy logic can

improve performance and adaptability in such technical applications by allowing systems to handle imprecise inputs more effectively.

'Fuzzy Logic' was ahead of its time in many respects, not least because it provided insights into the thinking necessary to power advancements in artificial intelligence. Kosko has since released an updated version of the book to underscore 'How AI Thinks in Shades of Gray'. The title is drawn from the fundamental premise that fuzzy logic challenges the traditional black-and-white binary thinking prevalent in classical logic and instead proposes a spectrum of possibilities – shades of gray⁴.

In many respects, fuzzy logic has found a home in AI systems, helping to handle uncertainty and

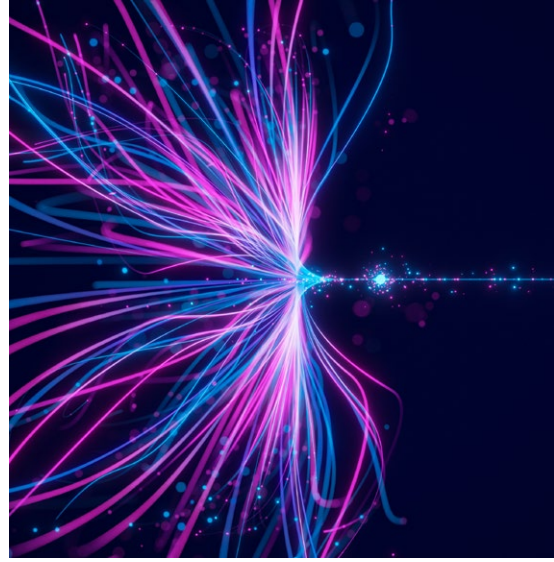
⁴ Bart Kosko (2024) Fuzzy Thinking: How AI Thinks in Shades of Gray. Fearless Books. www.amazon.co.uk/Fuzzy-Thinking-Bart-Kosko-ebook/dp/B0CBRXHHW8

Chapter 4: Fuzzy Thinking

variability and providing more nuanced and adaptable solutions than binary logic. The book also addresses the challenges posed by the opaque nature of contemporary AI systems, which often operate as 'black boxes' without providing clear explanations of their decision-making processes.

Fuzzy logic offers a solution to these challenges using rule-based systems that can be explained and audited. This concept extends to the field of explainable AI (XAI), which aims to make AI systems more transparent and accountable. Additionally, Kosko explores the use of fuzzy cognitive maps for modeling complex, causally entangled systems, making them valuable tools in both social sciences and engineering.

Overall, 'Fuzzy Thinking' advocates for a more nuanced and flexible approach to understanding and implementing logic, emphasizing the importance of embracing uncertainty and partial truths in both natural and artificial reasoning.



Now, when considering any system, you know that no matter how much you want it to be straightforward, actually, it's not that simple.

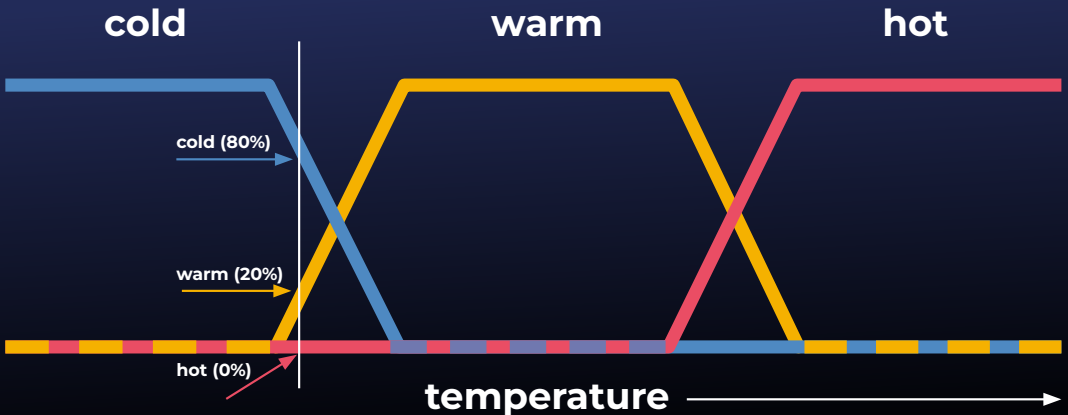


Fig. 4 Within fuzzy logic, meanings of cold, warm, and hot can be represented by functions on a temperature scale. A point on this scale has three truth values (i.e., one for each function). The vertical line shows a particular temperature that the arrows or truth values gauge: Red can be read as 'not hot', orange as 'slightly warm', and blue as 'fairly cold'. The degree of membership assigned for each fuzzy set is the result of fuzzification.

Personal response

What is vital in the design of mindful human-centered systems?

In human-centered systems, human skills are preserved and supported by technology to improve efficiency and effectiveness. The term 'mindful' encompasses a deeper awareness of the present moment, human emotions, and broader societal, environmental, and ethical considerations. Such systems should be designed with 1) empowerment and agency (i.e., respecting and empowering users by offering more control over interactions); 2) intentional design for user well-being (i.e., making the system easy to use and also promoting a healthier interaction between users and technology); 3) awareness of user impact (taking into account how its design affects users, both on a personal and collective level); 4) emotional and psychological sensitivity (recognizing that users come with diverse emotional states, hence the system should be empathetic and supportive); and 5) sustainability (promoting sustainable choices).

How can we engineer such mindful human-centered systems?

One can draw on the knowledge and experience of developing cognitive systems, especially in the areas of perception, learning and adaptation, or reasoning: 1) cognitive systems process data from sensors to recognize objects, interpret environments, and respond to real-time stimuli. For mindful systems, the perception of the 'here and now' is vital. 2) Cognitive systems are designed to learn from experience and adapt over time, improving their performance based on new data or feedback. This adaptability is crucial for mindful systems, as they need to adapt to user's changing needs or emotional state. 3) Cognitive systems can perform complex reasoning (deductive, inductive, or probabilistic) to solve problems

that involve both concrete tasks and more abstract reasoning. Mindful systems will be challenged with tasks that may require different reasoning styles. In short, I see mindful human-centered systems as cognitive systems 'on steroids'.

How can fuzzy sets, systems and logic help design such systems?

Important features of fuzzy sets and systems are that they can handle uncertainty, imprecision, and gradual transitions. Fuzzy sets, systems and logic can be used to ensure the following properties of a mindful human-centered system: 1) empowerment and agency (by providing explanations in natural language so the user can make a conscious decision to follow a recommendation or go against it); 2) emotional and psychological sensitivity (emotions can easily be modeled by the fuzzy sets and later processed by a fuzzy system); and 3) sustainability (making sustainable decisions requires dealing with many, often contradictory criteria). Fuzzy multi-criteria optimization enables users to compare various options and evaluate them. By explicit modeling those reasoning mechanisms, the system becomes more transparent and explainable, which in turn empowers the user.

Is it a way to build more ethical and trustworthy systems?

Responsibility for having more ethical and trustworthy systems can be approached from three perspectives. Put the responsibility with: 1) the system itself (thinking in terms of autonomous information systems); 2) the system designer; 3) the user, implying that we need methods that directly or indirectly support this user in using the system responsibly in an ethical and trustworthy manner.



Biography:

Anna Wilbik is Professor in Data Fusion and Intelligent Interaction at Department of Advanced Computing Sciences, Maastricht University and PI at Brightlands Institute for Smart Society, Maastricht University. Wilbik received her PhD in Computer Science from the Systems Research Institute, Polish Academy of Science in 2010. She was a Post-doctoral Fellow at University of Missouri, Columbia, USA and later an Assistant Professor at Eindhoven University of Technology, the Netherlands. Her research aims to bridge the gap between the meaning of data and human understanding in complex application environments, where data can be of various natures.



The journey so far, embracing the gray, and a framework for your next step.

Towards a Fuzzy Design Science Research framework

Computing with words and perceptions

As we bring this journey through fuzzy logic to a close, it's important to remember the primary purpose of this booklet: to offer a new way to think about and approach your research.

The path through this booklet has not been about offering simple answers but rather about encouraging you to rethink how you interact with uncertainty. Whether you are investigating human cognition, developing new technologies,

or studying complex systems like ecosystems or socio-economic networks, this booklet advocates embracing the gray areas where absolute precision is neither possible nor practical. This is where fuzzy logic, as we have explored in detail, becomes an invaluable tool.

The journey so far

In Chapter 1, we introduced the Principle of Incompatibility, which challenges traditional notions of scientific rigor by highlighting how



The aim is to expand manipulation of measurements to one of perceptions.

precision becomes elusive in complex systems. Lotfi Zadeh's revolutionary principle set the stage for understanding why the rigid tools of classical logic can fall short in addressing the intricate, fuzzy realities of the real world. As a graduate student, this lesson will fundamentally shape your research approach.

In Chapter 2, we saw how Design Science Research (DSR) offers a flexible methodology to tackle complex problems by iteratively creating and refining artefacts. This approach resonated with fuzzy logic's capacity to handle ambigu-

ity, as DSR does not demand absolute answers but encourages continuous improvement and learning through feedback loops. This iterative process is one that students can adopt in their own research, creating a dynamic space where mistakes are part of the learning process rather than something to avoid.

Chapter 3 expanded this thinking, introducing the idea of demo-driven innovation, which emphasizes experimentation and interaction with practical feedback. This model mirrors fuzzy logic's ability to operate under conditions of uncertainty and adapt to new information. This means developing and testing models in the real world, refining them based on what works, and being open to new insights that may emerge along the way.

In Chapter 4, we explored how Bart Kosko's work shattered traditional views of logic. Kosko reminded us that life rarely fits into neat, binary categories and that systems – especially those involving human thought and behavior – exist in shades of gray. Kosko's work on fuzzy logic illuminated the idea that knowledge and truth are not fixed binaries but fluid continua. This realization has profound implications for how we approach research and understanding, especially at the interface of system controls and human behavior.

Fuzzy logic and cognition

This is where we incorporate the insights of Enric Trillas from his work *The Genesis of Logic*⁵. Trillas' work reinforces what we've covered, particularly the understanding that human cognition and decision-making processes are not governed by binary logic but by a spectrum of possibilities.

In his work, Trillas argues that traditional models aim for control and precision. Fuzzy logic, on the other hand, allows for a more flexible and dynamic approach to modeling cognition and

⁵ Enric Trillas (2024): *The Genesis of Logic. Reflections on the Origins, Principles and Paths of Common-sense Reasoning*. Springer Cham. link.springer.com/book/10.1007/978-3-031-55040-9

decision-making. Fuzzy logic's capacity to represent and reason about uncertainty mirrors how humans naturally think and interact with complex systems.

One of the key insights from this work is that fuzzy logic provides a framework for managing 'unsharpness' in cognitive processes, helping us to formalize ambiguity and make meaningful decisions even in the face of incomplete or conflicting information. This approach can transform how you think about modeling real-world phenomena in your own research. Rather than striving for unattainable precision, you can use fuzzy logic to capture the nuanced, imprecise nature of the systems you're studying, and this can start with how you map out your research.

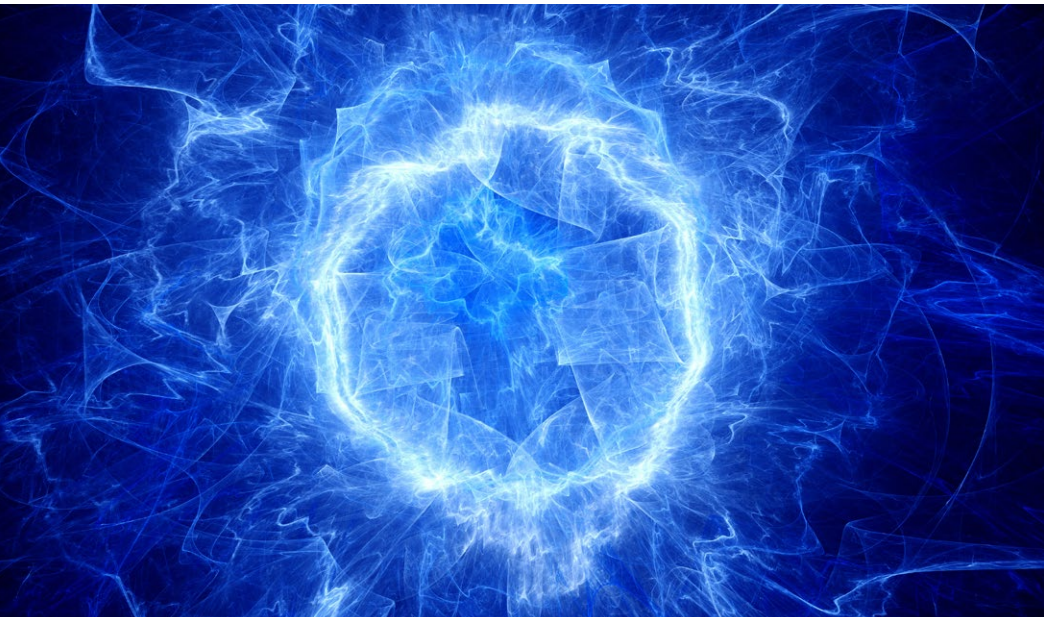
The Fuzzy Design Science Research framework

Figure 5 shows a framework for how fuzzy logic can be applied in research, guiding both the creation of practical knowledge and the generation of

new fuzzy theories. It's called Fuzzy Design Science Research (FDSR). This framework is an invaluable tool for you as a student, providing a structured yet flexible approach to navigating the complexity of research.

The FDSR framework begins with a practical problem – much like the starting point of any doctoral research. This practical problem, however, is not something that can be tackled using simple, binary thinking. As Lotfi Zadeh's Principle of Incompatibility taught us, the more complex the problem, the less useful rigid, binary solutions are. The FDSR framework encourages researchers to identify a research gap by asking, 'What is missing from a human perspective?' This recognizes that gaps in knowledge often involve uncertainty and ambiguity that traditional approaches fail to capture.

From there, the framework leads to formulating a research question and determining the appropriate research methodology, which, in the con-



text of fuzzy systems, may involve working with fuzzy logic to account for partial truths, overlapping categories, and degrees of uncertainty. The research process involves iterative refinement of the methodology, guided by feedback from real-world applications. As you move through this process, you will contribute both to practical knowledge and theoretical understanding, building a body of knowledge that is adaptive and responsive to the complexities of the real world.

Fuzzy Design Science Research combines fuzzy logic with natural language and common-sense reasoning, enabling computing with words and perceptions. This represents a shift from classical logic – where exact reasoning dominates – to a more flexible paradigm that aligns with how humans naturally think and communicate. This development is crucial for tackling the complex problems of today’s society, where interdisciplinary and transdisciplinary collaboration is critical to developing ethical and sustainable solutions.

Fuzzy approaches allow us to move from computing with numbers to computing with words.

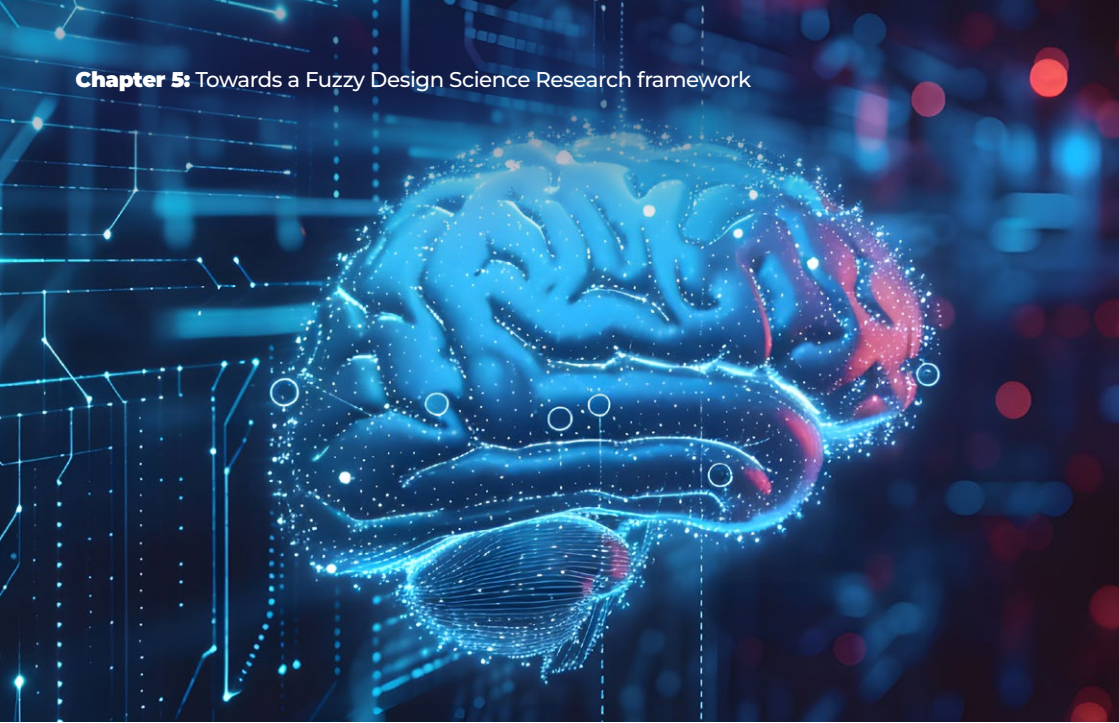
There are good reasons to use of words also in science: usually we use words when numbers are not known or too costly to obtain. Furthermore, we use words when they are good enough (i.e., when numbers are known and there is a tolerance for imprecision which can be exploited by employing words in place of numbers, thereby aiming at a reduction in cost and achieving simplicity). Last, we use words as linguistic summarizations, where words summarize numerical information.

Lean into the gray

Ultimately, the purpose of this booklet has been to challenge how you, as a graduate student, approach research. By understanding and em-



Fig. 5 Rooted in the Incompatibility Principle, Fuzzy Design Science Research combines fuzzy thinking with Design Science Research. Demo-driven innovation comprises design knowledge about means-end relationships between problem and solution spaces. This simple process enables us to handle not only numerical but also linguistic data. With it, we move from a measurement-based to perception-based Design Science Research.



bracing fuzzy logic, you are better equipped to handle the messy, uncertain realities of complex systems. Fuzzy logic doesn't seek to eliminate ambiguity or uncertainty but provides a means to work within it – turning these often-perceived challenges into strengths.

As Trillas argues, the future of fuzzy logic lies in its potential to create more robust models of human decision-making, governance, and social systems – areas where complexity and ambiguity reign. As a graduate student, you are entering a world where humanity's challenges are more interconnected and uncertain than ever before. Fuzzy logic offers you the tools to navigate this uncertainty, whether in academic research, industry, or policy.

This booklet has been designed to help you re-think how you approach research, particularly in the face of complexity and uncertainty. From the foundational concepts of the Principle of Incompatibility in Chapter 1 to the practical applications of Design Science Research and demo-driven

In science, there is a deep-seated tradition of according much more respect to numbers than to words.

– Lotfi Zadeh.

methodologies, we've explored how fuzzy logic can reshape your understanding of systems, decision-making, and problem-solving.

As you move forward in your journey, we encourage you to embrace the fuzziness inherent in your research. Instead of striving for unattainable precision, lean into the gray areas where the most profound insights are often waiting to be found. Uncertainty can lead to innovation, and using fuzzy logic can provide the tools to create meaningful, adaptable models of the complex systems you study. In doing so, you will not only navigate the intricacies of your research more effectively but also contribute to the growing body of knowledge that recognizes the power of ambiguity, flexibility, and interdisciplinary collaboration.

Personal response

How is your Soft and Cognitive Computing group at the Human-IST Institute, University of Fribourg, pursuing fuzzy design science research?

At the University of Fribourg, the Human-IST Institute focuses on human-centred interaction science and technologies in an inter- and transdisciplinary setting. We collaborate with our partners from business and government to explore the changes in society caused by digitisation. In doing so, we not only put emphasis on technology but also holistically integrate sustainability and ethics. The fuzzy design science research process enables us to do precisely this, for the benefit of our society. Our research partners are public service providers or the public sector who want to optimize citizens' quality of life, not merely the return on investment.

Your group is also researching ethics for the digital world. Can you tell us more about your approach to this, why it's needed, and the stakeholders involved?

In a digital world, we must ask ourselves how we want to live in today's age of artificial intelligence. After all, big data and machine learning are transforming increasingly more areas of our everyday lives. But the technology also comes at a price, because machine learning requires a lot of energy and is often related to a loss of privacy. For this reason, we focus on innovations

that take sustainability and ethics into account. For example, we are working on computing with words and perception models that can use small data in a similar way to our human brain, which means they require less energy and are also less invasive of privacy. With our research, we want to evolve from purely measurement-based to perception-based systems. Such systems can process our human values better and are particularly in demand from public service providers and the public sector.

How can integrative design be used to engineer ethical and sustainable technologies?

Integrative design means that we analyze and develop artefacts holistically. We look at engineering tasks through the lenses of different disciplines but also through the lenses of society as a whole. Our resulting artifacts, such as frameworks, mockups, and prototypes, thus become a lot more human. Our innovations are designed to empower people to reach a next level of mindfulness and not put them in a digital prison. To achieve this, we first must understand human values and integrate them into new technology. For this technology to be sustainable, today's bottleneck in AI's energy consumption must be overcome. We base our research on nature-inspired methods of soft computing, which include neural networks and evolutionary algorithms in addition to fuzzy logic. After all, we believe that intelligence is not artificial.



Biography:

Edy Portmann is professor of Computer Science and Artificial Intelligence at the University of Fribourg, co-director of the Human-IST Institute and president of the FMsquare Foundation. His research focuses on Computing with Words and Perceptions. After an apprenticeship as Electronics Technician, he studied Business Informatics and got a doctorate in Fuzzy Systems. He worked for Swisscom, PwC and EY, among others. In addition, he was also a researcher at the universities of Singapore, Berkeley and Bern.

Concluding remarks

by the Board of Trustees



One man recognized that the only way to truly think outside the box is to do away with the boxes themselves. By abandoning the rigid idea of 'true or false', Lotfi Zadeh redefined how we think about sets, logic and systems. At FMSquare Foundation, we apply this out-of-the-box thinking to our research projects. We believe that we all can learn from this thinking as long we are willing to take the risk of doing things a bit differently.

The Foundation is a new type of research initiative where professors, post-docs, and students, as well as other societal actors, collaboratively tackle the complexities of ethical and sustainable artificial intelligence to respect environmental limits and uphold social justice for present and future generations. Our formula to invent a sustainable future is a research environment that encourages researchers to ask questions that no one else has thought to ask.



While sound analysis of the problem at hand will remain paramount, attention has also increasingly been given to developing and implementing technical solutions. Our open research approach enables partner organizations to ask questions they would not have otherwise asked. The goal is for collaboration to help widen the front end of research and development pipeline

as well as spur innovative thinking about entirely new directions. And at the same time, the Foundation's interaction with business, government, and society helps it stay connected with real-world needs.

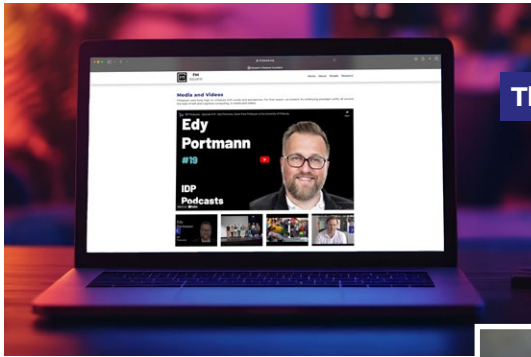
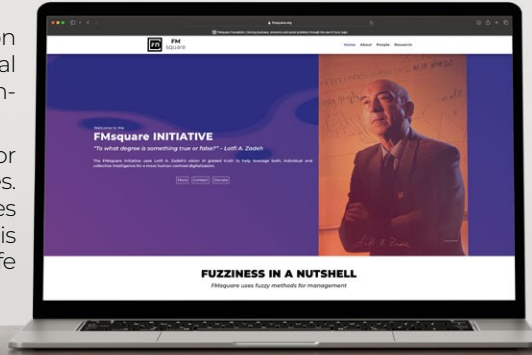
Sara D'Onofrio

Luis Téran

The FMsquare Initiative

The [FMsquare Initiative](#) uses Lotfi Zadeh's vision of graded truth to help leverage both individual and collective intelligence for a more human-centred digitalization.

It promotes fuzzy logic infinite truth values for business, governmental, and societal challenges. With its holistic approach, fuzzy logic combines biological and artificial intelligence and is inclusive, not exclusive. This mindset supports life in harmony with each other and with nature.

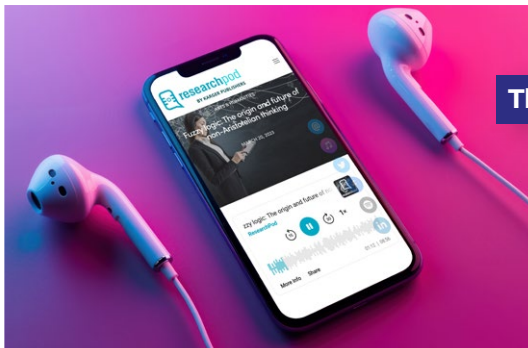
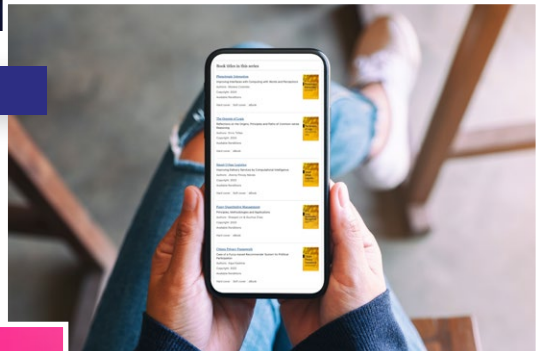


The FMsquare Video

See our [FMsquare Explanatory Video](#), which introduces the Foundation and its Initiative along with the benefits of Fuzzy Logic and Management Methods.

The FMsquare Book Series

Our [International FMsquare Book Series](#) spotlights the academic research efforts and findings of the FMsquare Initiative through the creation of engaging research books and textbooks on fuzzy management methods.



The FMsquare Podcasts

Listen to our exiting [FMsquare Podcasts](#) where our research is presented and explained in a short and concise manner.

For more information, visit our FMsquare website:





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