

**RESEARCH METHODOLOGY**

Research methodology is the systematic approach and analysis of the methods applied to a field of study. It encompasses the overall approach to systematically solving the research problem and guides how research is conducted, ensuring that the research findings are valid, reliable, and replicable. A qualitative approach is used to build the conceptual foundations and to identify the factors influencing I4.0 adoption in global supply chains. Multi criteria decision making (MCDM) approach is used to model the interrelationships among various factors. The qualitative approach is used to frame recommendations to build a suitability model for I4.0 adoption in global supply chains. In the quantitative approach, a suitability model as a mixed integer nonlinear program (MINLP) is formulated and solved.

**3.1 Research Framework**

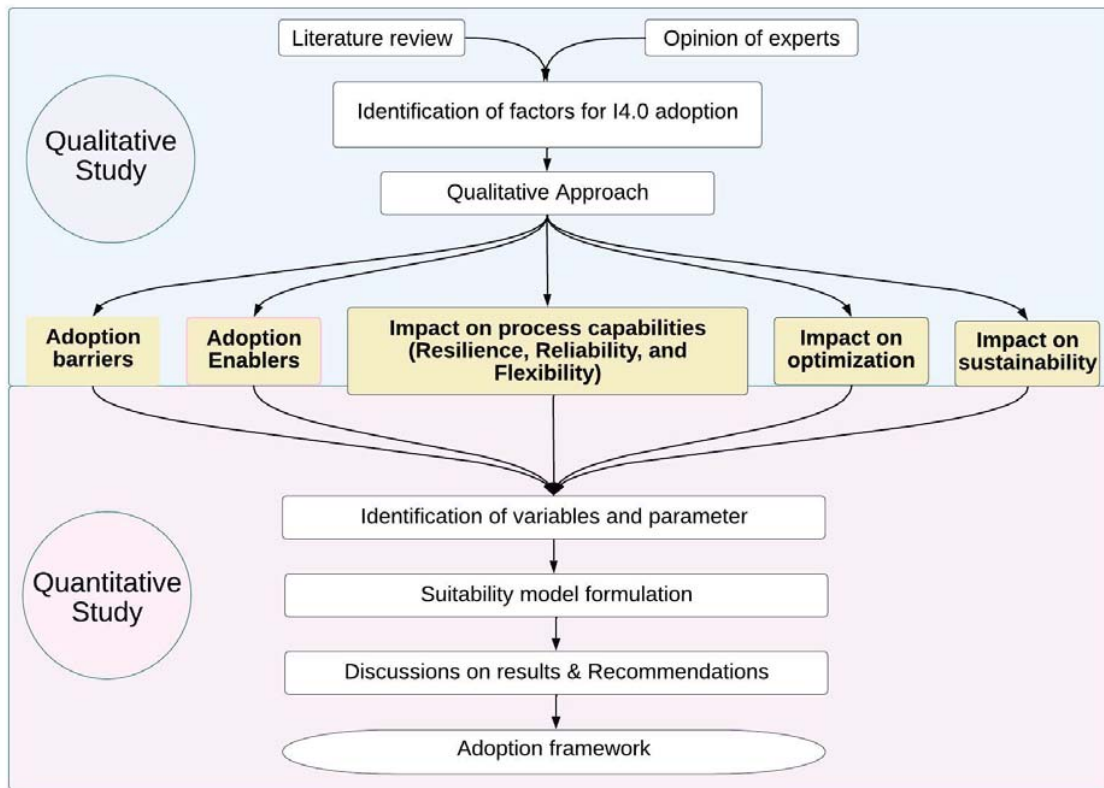


Figure 4: Research framework

Figure 4 shows the research framework adopted to conduct the study. A comprehensive literature review along with the opinion of experts is performed to identify the research gaps and research questions. Further, the research objectives are framed and factors influencing I4.0 are identified. In the next step MCDM approach is used to explore the interrelations among all influencing factors. Further in the study, the impact on supply chain capabilities such as resilience, reliability, and flexibility are analyzed in the context of sustainability. In the quantitative approach, a suitability model as a mixed integer nonlinear program (MINLP) is formulated which majorly considers cost optimization and sustainability.

### 3.2 Research Design

A five-phase research design approach is adopted, as illustrated in Figure 5. In Phase 1, the problem context and specific goals are outlined. Phase 2 provides a comprehensive overview of previous research in the field. Following this, Phase 3 focuses on qualitative analysis, which helps us understand the current state of the industry 4.0 adoption. In Phase 4 quantitative analyses are performed, Finally, Phase 5 showcases the results and analysis of our findings.

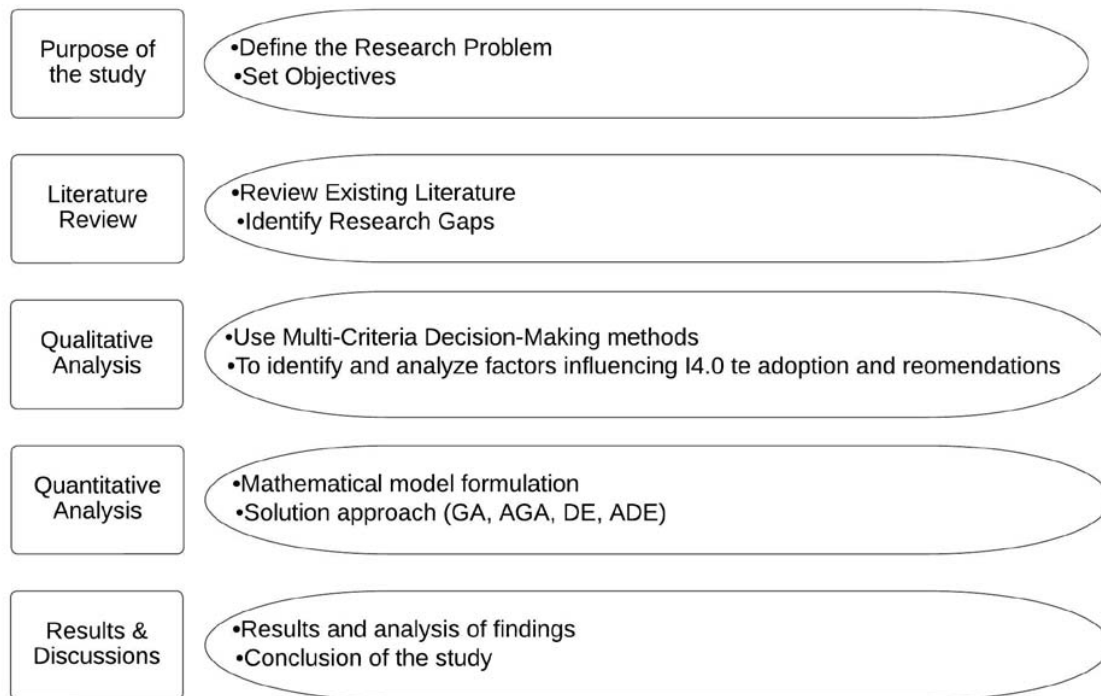


Figure 5: Research Design

### **3.3 Qualitative Analysis:**

The MCDM approaches used in this study are summarised below. The detailed steps are discussed in forthcoming chapters.

#### **3.3.1 Grey-DEMATEL (Decision Making Trial and Evaluation Laboratory) method:**

This method allows us to investigate the impact of critical success factors and to obtain the cause/effect relationship of I4.0 adoption enablers and barriers. Sensitivity analysis is performed to assess the robustness of the obtained results. DEMATEL is one of the best approaches for analyzing cause/effect relationships in complicated models, which is one of the main benefits of utilizing this approach, however, it fails to comprehend the uncertain situations or lack of information (Gupta & Barua, 2018). Thus, the grey approach is combined with DEMATEL to address this issue. The Grey approach works well with limited data under vagueness. In addition, the successful application of the grey DEMATEL method in various fields of supply chain makes it a suitable approach for the proposed study.

#### **3.3.2 AHP- DEMATEL- PROMETHEE II:**

Analytical Hierarchy Process (AHP) is used to structure the complexity of benchmarking enablers of I4.0 hierarchically as it helps in evaluating multiple criteria. In addition, the AHP approach utilizes the pairwise comparisons technique thus assisting in the proper analysis of enablers (Teng et al., 2023). Further to understand the causal relations among enablers, DEMATEL technique is employed as it is a powerful technique to analyze and visualize the intricate systems and to provide detailed insights into the interactions among enablers (Zhang et al. 2023). Further to obtain the preference and ranking of enablers benchmarking enablers PROMETHEE II is used (Ridha et al., 2023). These methods are versatile and can be applied in various domains. In addition, they provide a robust framework for efficient decision making thus enabling the researchers to systematically understand the multiple criteria and complex interrelations among various factors.

#### **3.3.3 ISM-Fuzzy-ANFIS:**

To analyze the role of I4.0 adoption enablers for supply chain flexibility and its impacts on resilience and sustainability this study incorporates an integrated approach consisting of Interpretive structural modeling, fuzzy, and Adaptive Neuro-Fuzzy Inference Systems (ANFIS)

to the intricacies of building flexible practices for resilient and sustainable supply chains through I4.0 for societal and economic development.

### **3.4 Quantitative Analysis:**

The recommendations from qualitative analysis are employed to identify sustainable supply chain cost parameters. The obtained scenario is formulated using mixed integer nonlinear programming (MINLP) and a robust model for supply chain networks to delve into the impact and strategic adoption of I4.0 for cost optimization and the reduction of scope 1, 2, and 3 carbon footprints is developed. An industrial case of an electronic supply chain is considered to solve the proposed model. The proposed model is solved using genetic algorithm (GA), adaptive genetic algorithm (AGA), differential evolution (DE), and adaptive differential evolution (ADE) approaches. This is a complex combinatorial problem which makes it computationally challenging to solve as the number of possible solutions grows exponentially with the problem size and is difficult to solve with commercially available solvers. This type of problem is stated as NP-hard by many researchers such as Feng et al. (2021), Maroof et al. (2024), Gan, Q. (2022), and Zhang et al. (2024). In addition, the problem under study involves rule-based heuristics for the adoption of I4.0 technologies in three different levels which depends on the quantity processed by each stakeholder and it cannot be solved by exact solvers such as Gurobi and CPLEX. Therefore, this study used the Genetic algorithm (GA), Adaptive Genetic algorithm (AGA), Differential Evolution (DE), and Adaptive Differential Evolution (ADE) to obtain the optimal solution.