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Design and Analysis of Digital Control Buck Converter for optimum performance

Nur Ain Elisa Razali*, and A.H.M Zahirul Alam

Dept of Electrical and Computer Engineering, International Islamic University Malaysia, Kuala Lumpur, Malaysia

*Corresponding author: rzalielisa@gmail.com

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Abstract— This paper aims to design and analyze a digitally controlled buck converter meant for applications requiring DC voltage under varying input voltages and load conditions. The buck converter is designed with a switching frequency of 40 kHz, an inductor value of 200 µH, and a capacitor of 100 µF with Pulse Width Modulation (PWM). The Proportional-Integral (PI) controller is used to maintain the output voltage steady. For simulation and performance evaluation, PSpice and MATLAB/Simulink software are selected. This paper aims to create a digital control system that is better than the traditional analog controllers, offering precise and adaptive regulation. The simulation results highlight how effective the digital PI controller is at reducing voltage ripple and maintaining the output voltage, even when the inputs and loads vary. This study covers detailed parameter calculations, controller design, circuit simulation, and performance analysis, providing a thorough overview of the digitally controlled buck converter system.

Keywords: *Buck Converter, MATLAB, PSpice, Pulse Width Modulation (PWM), and PI controller*

1. INTRODUCTION

The modern electronic devices rely heavily on having a consistent supply voltage, which is where voltage regulators come into play. Among these, DC-DC converters are essential in power electronics, converting an unregulated DC input into a regulated DC output using various techniques. The ability to efficiently manage power between different voltage levels is crucial in applications ranging from consumer electronics to industrial systems [1].

One of the standout topologies in this realm is the buck converter, often referred to as a step-down DC-DC converter. Buck converters are prized for their efficiency, compact size, and their ability to fit into battery-powered and space-limited applications. The increasing demand for higher efficiency and miniaturization in electronic devices has propelled the global DC-DC converter market, making research in this field more important than ever[2].

To boost the performance of buck converters, it's crucial to implement advanced control mechanisms. The Proportional Integral (PI) controller is famous as it effectively reduces the voltage output fluctuation and enhances the transient response [2]. PI controllers help by responding more swiftly to load changes and achieving better overall stability. Despite widespread use, buck converters still face a number of ongoing challenges. Some of the main issues include energy loss, voltage instability, difficulties with thermal management, and electromagnetic interference (EMI), which can affect performance and reliability [3].

Traditional analog control circuits often find it tough to maintain high performance when input voltages vary and load conditions change. The output voltage's sensitivity to duty-cycle variations calls for strong control strategies to ensure stable operation, particularly when input conditions are inconsistent. This paper presents to design of a buck converter suitable for general-purpose DC voltage regulation in both low-power and high-power

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systems, to develop a digital control system for the designed buck converter, and to analyze the performance of the buck converter equipped with this digital control system.

Previous researchers have mentioned various control strategies for buck converters, such as Proportional-Integral (PI) controllers [2], Sliding Mode Control (SMC) [4], and Fuzzy Logic control [1]. Yet, these methods often face limitations in dynamic environments or require complicated analog circuitry. This study offers a solution by implementing a digital control system that utilizes PWM and PI control theories, aiming to reduce peak currents during transients and improve both reliability and efficiency [2]. The approach builds upon and extends the findings of prior works, offering a digitally controlled buck converter with broad applicability and optimized performance for contemporary electronic systems

2. DESIGN OF CONVERTER

The methodology includes calculating essential parameters, choosing the right components, developing a digital control system, and running thorough simulations using MATLAB/Simulink and PSpice. The entire process is organized to ensure that it can be simulated and the performance can be analyzed under different conditions.

2.1 Buck Converter System

2.1.1. Design Specifications

The converter is designed to reduce a 24V DC input down to a stable 6V DC output, making it suitable for various low- and high-power applications. A switching frequency of 40 kHz has been chosen to strike a balance between efficiency and component size while minimizing output voltage ripple. To find the required duty cycle, D, the standard buck converter is in Eqn (1),

$$D = \frac{V_{OUT}}{V_{IN}} \tag{1}$$

Next, determine the inductor value (L) to keep the inductor current ripple within 10% of the maximum load current, as shown in Eq. (2) is determined. The calculated value for L is 93.75 µH.

$$L = \frac{V_g\,(1-D)\,D \times \frac{1}{f_S}}{\Delta I_L \times 2} \tag{2}$$

The ripple current and voltage must stay below the maximum specification limit of the capacitor [5]. The output capacitor (C) is selected to keep the output voltage ripple to just 1% of V_{out} as indicated in Eq. (3).

$$C = \frac{\Delta I_L}{(\Delta V_{OUT} \times f_S \times 8)} \tag{3}$$

MOSFET is chosen for its quick switching capabilities and low on-resistance as the switch, a Schottky diode for its low forward voltage drop and high switching speed [6], and a load resistance that varies from 1Ω to 1kΩ during simulations to evaluate the circuit's robustness.

2.1.2. Controller Design

To get the precise output voltage, Pulse Width Modulation (PWM) is important in controlling the switching of the MOSFET. In this project, a PI controller is used to tune the PWM signal by adjusting the duty cycle, D, to reduce the steady-state error and enhance the transient response.

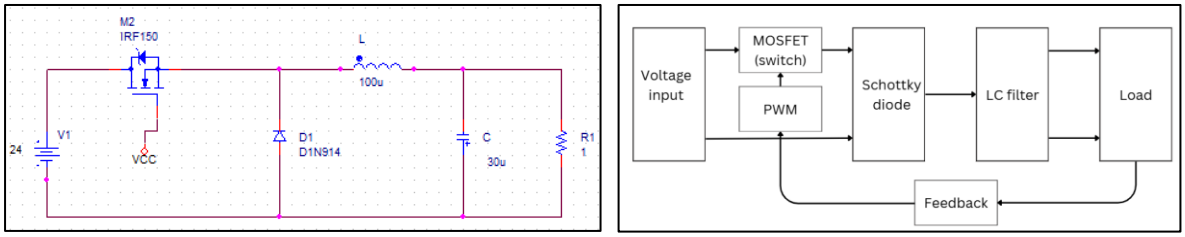
2.2 Simulation and Analysis

2.2.1 Simulation Tools

PSpice is used to design a detailed circuit, validate the switching behavior, and analyze the component interaction. MATLAB/Simulink, on the other hand, is important when designing the PI controller and analyzing the results.

2.2.2 Circuit Design and Control Logic

The converter circuit is built in PSpice and also MATLAB/Simulink, integrating the calculated values for inductance (L) and capacitance (C), along with the MOSFET switch, Schottky diode, and a variable load. The PWM and PI controllers are implemented using MATLAB/Simulink, where feedback from the output voltage is used to dynamically adjust the PWM duty cycle. To ensure the simulation runs optimally, various combinations of inductance and capacitance are tested. Table 2.1 summarizes the results, with L set at 200 µH and C at 100 µF chosen for the final MATLAB model due to their excellent transient and steady-state characteristics.



a) b)

Fig 1. a) Schematic diagram for the buck converter, b) detailed Internal Block Diagram of a Buck Converter

2.2.3 Parameter Optimisation

To ensure optimal performance in simulation, various combinations of inductance and capacitance are tested. Table 3.1 summarises the results, with L = 200 µH and C = 100 µF selected for the final MATLAB model due to their superior transient and steady-state characteristics.

Table. 1 Design parameters C and L, and the output responses for different values of C and L

L (µH)	C (µF)	$\Delta I_L\,(A)$ (< 0.6)	$I_L\,(peak)(A)$	$I_L\,(rms)$	I_{CIN}	ESR	$\Delta V_{out}(V)$ (< 0.06)
100	30	1.125	6.5625	6.0088	2.2733	- 0.0508	0.0600
150	30	0.750	6.375	6.0039	2.2604	- 0.0242	0.0599
200	30	0.5625	6.2813	6.0022	2.2559	0.0025	0.06
200	68	0.5625	6.2813	6.0022	2.2559	0.0607	0.0599
200	100	0.5625	6.2813	6.0022	2.2559	0.0754	0.0599

2.2.4 Simulation Configuration

The solver type is carefully chosen to accurately model the fast-switching events and dynamic response of the control system. Additionally, the sampling frequency is set equal to the switching frequency of 40 kHz to enable precise emulation of the digital control signals and maintain synchronization with the MOSFET switching.

2.2.4 Execution and Data Analysis

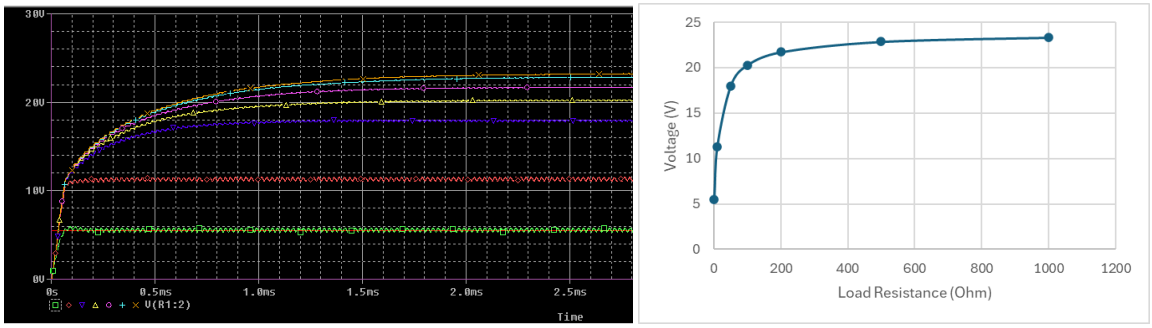
Simulation has been done to observe and record the stability of the output voltage and ripple, as well as the waveforms of the inductor current. The system responds to sudden changes in load resistance, ranging from 1Ω to 1kΩ, to assess its robustness. The results from these simulations help to validate the initial design.

3. RESULTS AND DISCUSSION

The results are based on the PSpice and MATLAB/Simulink by showing how the converter behaves under a variety of ideal and non-ideal conditions, such as changes in load resistance, capacitance, inductance, duty cycle, and input voltage, along with the effects of parasitic resistances and diode forward voltage drops.

3.1 PSpice Simulations

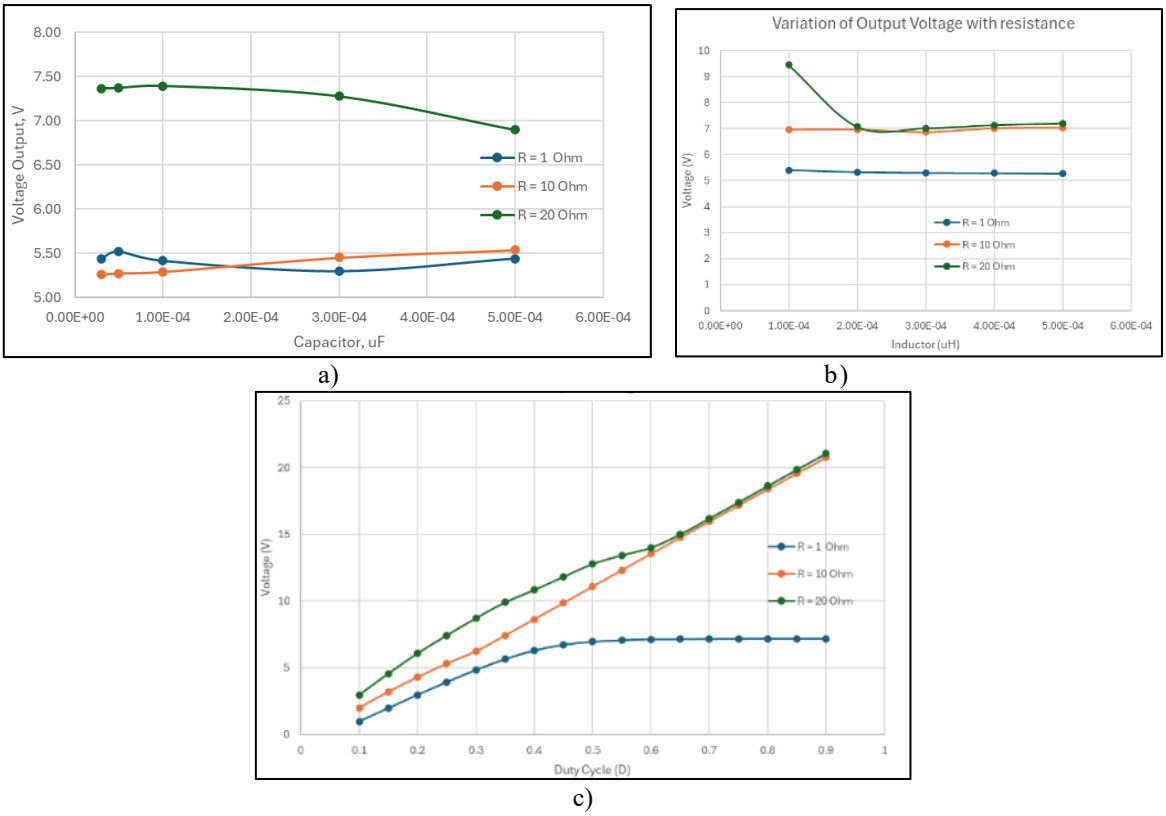
PSpice simulations using practical approximations for the calculated inductor L = 100 µH and capacitor C = 30 µF values have been carried out. These simulations were designed to help understand how the buck converter performs across different operating conditions.



a) b)

Fig. 3. Sweep Analysis with Varying Load in a) PSpice, b) Excel

Figure 3 shows that as the load resistance increased from 1Ω to 1 kΩ, the output voltage also increased because a higher load resistance draws less current from the converter. Thus, reduces voltage drops across internal components like the inductor's resistance and the switch. This highlights the importance of having a controller to keep the output voltage stable, even with different loads.



a) b)

c)

Fig. 4 Output voltage variation with the variation of (a) Capacitance, (b) Inductance, and (c) Duty cycle

Figure 4 shows the results for voltage output by varying the capacitance, inductance, and also the duty cycle in the PSpice.

The Fig. 4 (a) shows the capacitance from 30 µF to 500 µF with L=100 µH. The results show that higher capacitance increases the output voltage stability by reducing ripple. A bigger capacitor does a better job of holding the voltage steady during those switching and load changes.

The Fig. 4 (b) shows the inductance value ranging from 100 µH to 500 µH with C= 30 µF. The output voltage stability improved, and the current ripple was reduced, especially for low-resistance loads. Even with lower loads, the higher inductance delivered a smoother output, although the effects weren't as dramatic.

Fig. 4 (c) shows that the output voltage increases with the duty cycle, which aligns with an ideal buck converter. However, at lower resistances like 0.1 Ω, the higher current led to increased losses in the switch, inductor, and wiring. This caused noticeable deviations from the ideal output, highlighting the importance of considering real-world losses in the design. In this design, the lowest resistance value that the PI controller can manage is 0.1 Ω, while the highest is 2 kΩ.

3.2 MATLAB Simulations

The MATLAB/Simulink was used, which included implementing a Proportional-Integral (PI) controller to regulate the output voltage, and the block diagram is shown in Fig. 5. The best L and C values for our MATLAB simulations are 200 µH and 100 µF, respectively, as they struck a great balance between low current ripple and minimal output voltage ripple.

3.2.1 Ideal Case

In the ideal case, simulations were performed without accounting for real-world losses or imperfections.

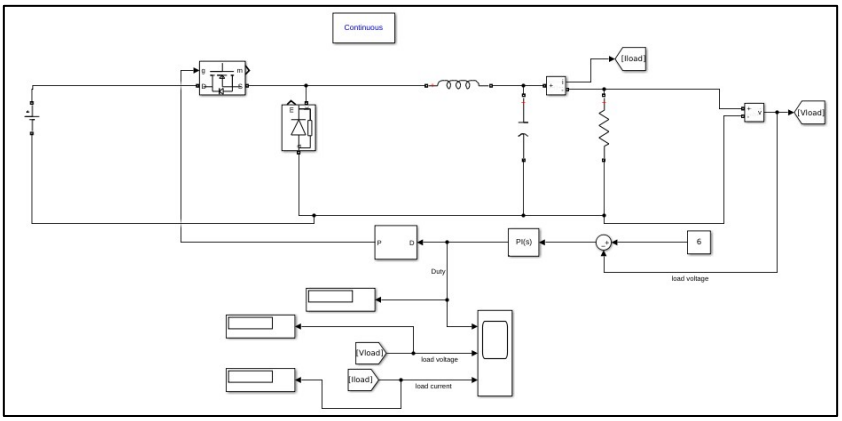


Fig.5. Buck converter schematic diagram with the PWM

The ideal buck converter output voltage is 5.831 V at a duty cycle of 0.2746 before turning on the PI controller. After tuning, the output voltage increases to 5.994 V with a duty cycle of 0.281 with the same load resistance. The PI values are 0.290 and 75.119, respectively, which means the duty cycle will quickly react to voltage changes and eliminate steady-state errors, thus ensuring the output voltage remains close to the desired 6 V. Figure 6 shows the variation of voltage output with capacitance. 100 µF results in the most stable voltage output compared to 30 µF and 68 µF. This shows that a higher capacitance minimizes voltage ripple and helps manage sudden load changes.

As expected, the current naturally decreased as resistance increased for all capacitance values, following Ohm's law. The fact that the output voltage remained constant, even with changes in current, highlights the importance of having larger capacitors to store energy. We also observed that the duty cycle dropped with rising resistance across all capacitance values, which makes sense given the lower current demand. The 100 µF capacitor's smoother and more consistent duty cycle curve indicates a better response and regulation.

Next, when simulating different values of input voltages, 24 V, 50 V, and 100 V with 1Ω load resistance, the voltage output stayed reliably close to 5.99 V. As the voltage input increased duty cycle value decreased to keep the output voltage steady at higher input levels. This result aligns with the buck converter's ideal equation. Throughout this process, the output current remained fairly stable, ensuring a consistent delivery to the load.

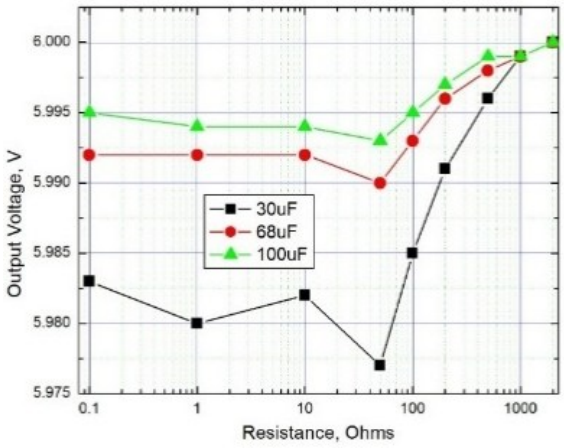


Fig. 6. Variation of the Output Voltage with Capacitance

3.2.2 Non-Ideal Case

Simulations were performed to analyse the circuit's behaviour in a non-ideal environment, considering parasitic resistances and diode forward voltage drops as shown in Fig. 7.

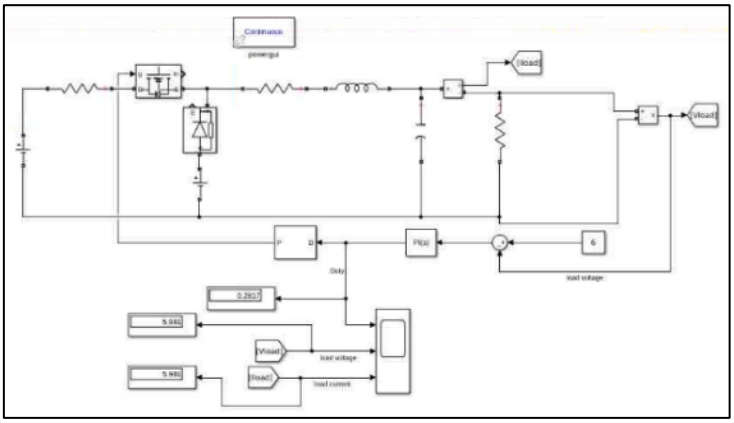


Fig. 7. Non-ideal Buck converter schematic diagram

Introducing a 50 mΩ series resistance before the inductor resulted in a slight dip in output voltage and current, particularly when the load resistance was low, thanks to those pesky I^2R losses. To make up for this, the converter ramped up the duty cycle. On a similar note, adding 50 mΩ resistance at the MOSFET also caused voltage and current drops under heavy loads, again due to increased losses. Plus, opting for a diode with a higher forward voltage of 0.7 V compared to 0.2 V further reduced output voltage and current during heavy loads, showcasing the efficiency perks of low V_f Components.

When accounting for diode losses, the ideal buck converter output voltage can be expressed in Eqn. 4.

$$V_{out} = D \times V_{in} - V_f \tag{4}$$

Thus, for V_f = 0.2 V, Vout was 5.8 V, and for V_f = 0.7 V, Vout dropped to 5.3 V.

The duty cycle had to increase to maintain the desired output voltage when diode losses were present. The modified duty cycle expression,

$$D = \frac{V_{out}+V_f}{V_{in}} \quad (5)$$

showed that for V_f= 0.2 V, D = 0.2583, and for V_f= 0.7 V, D = 0.2792. This clearly shows that a higher V_f means a higher duty cycle is needed to make up for the voltage lost during the off cycle. If all non-ideal factors are taken into account, the drop in output voltage and current becomes even more noticeable, and the duty cycle increases more dramatically.

The general buck converter equation, $V_{out} = D \times V_{in} - I \times R_{Total} - V_{Diode}$ effectively captures the behavior we observed, where R_{Total} includes the resistances of the MOSFET and the inductor. These simulations really underscore the vital need to consider component non-idealities in real-world converter designs to ensure they operate accurately and efficiently.

Table 2. The output values for a non-ideal simulation with load resistance 10Ω.

Non-ideal	Inductor		MOSFET		Diode		Combined			
	10mΩ	50mΩ	10mΩ	50mΩ	0.2V	0.7V	0.2V		0.7V	
							10mΩ	50mΩ	10mΩ	50mΩ
V_{out}, V	5.994	5.994	5.994	5.994	5.994	5.994	5.995	5.995	5.995	5.995
Current, A	0.5994	0.5994	0.5994	0.5994	0.5994	0.5994	0.5994	0.5994	0.5995	0.5995
Duty Cycle, D	0.2749	0.2759	0.2747	0.2748	0.2686	0.2534	0.2691	0.2702	0.2538	0.255

4. CONCLUSION

This paper provided a detailed look at the design process, covering key parameters like duty cycle, switching frequency, inductor and capacitor values, and the best choices for components. Since the buck converter was designed for general-purpose DC voltage regulation, it is suitable for both low-power and high-power applications. Additionally, a digital control system was effectively developed for the converter. The performance of this buck converter, with its digital control system, was examined and analysed through simulations using PSpice and MATLAB/Simulink. The research specifically chose Pulse Width Modulation (PWM) as the modulation technique, with its behaviour tuned by a Proportional-Integral (PI) controller to ensure precise output voltage. The simulations consistently showed that this control approach leads to a solid level of stability and impressive system performance for the digitally controlled buck converter.

REFERENCES

[1] 2021 18th International Multi-Conference on Systems, Signals & Devices (SSD), Monastir, Tunisia: IEEE, Mar. 2021, pp. 1419-1424. https://doi.org/10.1109/SSD52085.2021.9429371

[2] H. Sucu, T. Göktaş, and M. Arkan, "Design, Simulation and Application of Buck Converter with Digital PI Controller," Balk. J. Electr. Comput. Eng., vol. 9, no. 2, Art. no. 2, Apr. 2021. https://doi.org/10.17694/bajece.884290

[3] Gao, Linghao. (2025). Review of DC-DC Converters: Analysis and Applications of Buck and Boost Converters. Applied and Computational Engineering. 148. 14-18. https://doi.org/10.54254/2755-2721/2025.22314

[4] J. Linares-Flores et al., "Sliding Mode Control Based on Linear Extended State Observer for DC-to-DC Buck-Boost Power Converter System With Mismatched Disturbances," IEEE Trans. Ind. Appl., vol. 58, no. 1, pp. 940-950, Jan. 2022. https://doi.org/10.1109/TIA.2021.3130017

[5] Current waveform of each part. (1). Page 2. 2/6. Application Note. Capacitor Calculation for Buck converter IC. © 2012 ROHM Co., Ltd. No. 61AN104E Rev.004.https://fscdn.rohm.com/en/products/databook/applinote/ic/power/switching_regulator/capacitor_calculation_appli-e.pdf

[6] R. W. Erickson and D. Maksimović, Fundamentals of Power Electronics. Cham: Springer International Publishing, 2020. https://doi.org/10.1007/978-3-030-43881-4