Economic Burden of Personal Protective Strategies for Dengue Disease: an Optimal Control Approach

International Conference on Optimization, Learning Algorithms and Applications

OL2A 2021: Optimization, Learning Algorithms and Applications pp 319-335 | Cite as

- Artur M. C. Brito da Cruz (1) (3) View author's OrcID profile (View OrcID profile)
- Helena Sofia Rodrigues (2) (3) Email author (sofiarodrigues@esce.ipvc.pt)View author's OrcID profile (View OrcID profile)

1. Escola Superior de Tecnologia de Setúbal, Instituto Politécnico de Setúbal, , Setúbal, Portugal
2. Escola Superior de Ciências Empresariais, Instituto Politécnico de Viana do Castelo, , Valença, Portugal
3. CIDMA - Centro de Investigação e Desenvolvimento em Matemática e Aplicações, Departamento de Matemática, Universidade de Aveiro, , Aveiro, Portugal

Conference paper
First Online: 01 January 2022

Part of the Communications in Computer and Information Science book series (CCIS, volume 1488)

Abstract

Dengue fever is a vector-borne disease that is widely spread. It has a vast impact on the economy of countries, especially where the disease is endemic. The associated costs with the disease comprise prevention and treatment. This study focus on the impact of adopting individual behaviors to reduce mosquito bites - avoiding the disease's transmission - and their associated costs. An epidemiological model is presented with human and mosquito compartments, modeling the interaction of dengue disease. The model assumed some self-protection measures, namely the use of repellent in human skin, wear treated clothes with repellent, and sleep with treated bed nets. The household costs for these protections are taking into account to study their use. We conclude that personal protection could have an impact on the reduction of the infected individuals and the outbreak duration. The costs associated with the personal protection could represent a burden to the household budget, and its purchase could influence the shape of the infected's curve.

Keywords

Dengue Economic burden Personal protection Household costs
Optimal control

Supported by FCT - Fundação para a Ciência e a Tecnologia.

Notes

Acknowledgement

This work is supported by The Center for Research and Development in Mathematics and Applications (CIDMA) through the Portuguese Foundation for Science and Technology (FCT - Fundação para a Ciência e a Tecnologia), references UIDB/04106/2020 and UIDP/04106/2020.

References

1. Bhatt, S., et al.: The global distribution and burden of dengue. Nature **496**, 504–507 (2013)
CrossRef (https://doi.org/10.1038/nature12060)
Google Scholar (http://scholar.google.com/scholar_lookup?title=The%20global%20distribution%20and%20burden%20of%20dengue&author=S.%20Bhatt&journal=Nature&volume=496&pages=504-507&publication_year=2013)

2. Brito da Cruz, A.M., Rodrigues, H.S.: Personal protective strategies for dengue disease: simulations in two coexisting virus serotypes scenarios. Math. Comput. Simul. **188**, 254–267 (2021)
MathSciNet (http://www.ams.org/mathscinet-getitem?mr=4249140)
CrossRef (https://doi.org/10.1016/j.matcom.2021.04.002)
Google Scholar (http://scholar.google.com/scholar_lookup?title=Personal%20protective%20strategies%20for%20dengue%20disease%3A%20simulations%20in%20two%20coexisting%20virus%20serotypes%20scenarios&author=AM.%20Brito%20da%20Cruz&author=HS.%20Rodrigues&journal=Math.%20Comput.%20Simul.&volume=188&pages=254-267&publication_year=2021)

3. Cesari, L.: Optimization-Theory and Applications. Springer, New York (1983)
CrossRef (https://doi.org/10.1007/978-1-4613-8165-5)
Google Scholar (http://scholar.google.com/scholar_lookup?title=Optimization-Theory%20and%20Applications&author=L.%20Cesari&publication_year=1983)

4. Chan, M., Johansson, M.A.: The incubation periods of dengue viruses. PLoS One 7(11), e50972 (2012)
CrossRef (https://doi.org/10.1371/journal.pone.0050972)
Google Scholar (http://scholar.google.com/scholar_lookup?title=The%20incubation%20periods%20of%20dengue%20viruses&author=M.

%20Chan&author=MA.%20Johansson&journal=PLoS%20One&volume=7&issue=11&pages=e50972&publication_year=2012)

5. Demers, J., Bewick, S., Calabrese, J., Fagan, W.F.: Dynamic modelling of personal protection control strategies for vector-borne disease limits the role of diversity amplification. J. R. Soc. Interface **15**, 20180166 (2018)
CrossRef (https://doi.org/10.1098/rsif.2018.0166)
Google Scholar (http://scholar.google.com/scholar_lookup?title=Dynamic%20modelling%20of%20personal%20protection%20control%20strategies%20for%20vector-borne%20disease%20limits%20the%20role%20of%20diversity%20amplification&author=J.%20Demers&author=S.%20Bewick&author=J.%20Calabrese&author=WF.%20Fagan&journal=J.%20R.%20Soc.%20Interface&volume=15&pages=20180166&publication_year=2018)

6. Focks, D.A., Brenner, R.J., Hayes, J., Daniels, E.: Transmission thresholds for dengue in terms of Aedes aegypti pupae per person with discussion of their utility in source reduction efforts. Am. J. Trop. Med. Hyg. **62**, 11–18 (2000)
CrossRef (https://doi.org/10.4269/ajtmh.2000.62.11)
Google Scholar (http://scholar.google.com/scholar_lookup?title=Transmission%20thresholds%20for%20dengue%20in%20terms%20of%20Aedes%20aegypti%20pupae%20per%20person%20with%20discussion%20of%20their%20utility%20in%20source%20reduction%20efforts&author=DA.%20Focks&author=RJ.%20Brenner&author=J.%20Hayes&author=E.%20Daniels&journal=Am.%20J.%20Trop.%20Med.%20Hyg.&volume=62&pages=11-18&publication_year=2000)

7. Focks, D.A., Haile, D.G., Daniels, E., Mount, G.A.: Dynamic life table model for Aedes aegypti (Diptera: Culicidae): analysis of the literature and model development. J. Med. Entomol. **30**, 1003–1017 (1993)
CrossRef (https://doi.org/10.1093/jmedent/30.6.1003)
Google Scholar (http://scholar.google.com/scholar_lookup?title=Dynamic%20life%20table%20model%20for%20Aedes%20aegypti%20%28Diptera%3A%20Culicidae%29%3A%20analysis%20of%20the%20literature%20and%20model%20development&author=DA.%20Focks&author=DG.%20Haile&author=E.%20Daniels&author=GA.%20Mount&journal=J.%20Med.%20Entomol.&volume=30&pages=1003-1017&publication_year=1993)

8. Goodman, C.A., Mnzava, A.E.P., Dlamini, S.S., Sharp, B.L., Mthembu, D.J., Gumede, J.K.: Comparison of the cost and cost-effectiveness of insecticide-treated bednets and residual house-spraying in KwaZulu-Natal, South Africa. Trop. Med. Int. Health **6**(4), 280–95 (2001)
CrossRef (https://doi.org/10.1046/j.1365-3156.2001.00700.x)
Google Scholar (http://scholar.google.com/scholar_lookup?title=Comparison%20of%20the%20cost%20and%20cost-effectiveness%20of%20insecticide-treated%20bednets%20and%20residual%20house-spraying%20in%20KwaZulu-Natal%2C%20South%20Africa&author=CA.%20Goodman&author=AEP.%20Mnzava&author=SS.%20Dlamini&author=BL.%20Sharp&author=DJ.%20Mthembu&author=JK.%20Gumede&journal=Trop.%20Med.%20Int.%20Health&volume=6&issue=4&pages=280-95&publication_year=2001)

9. Hariharana, D., Dasb, M.K., Sheparda, D.S., Arorab, N.K.: Economic burden of dengue illness in India from 2013 to 2016: a systematic analysis. Int. J. Infect.

Dis. **84S**, S68–S73 (2019)
CrossRef (https://doi.org/10.1016/j.ijid.2019.01.010)
Google Scholar (http://scholar.google.com/scholar_lookup?title=Economic%20burden%20of%20dengue%20illness%20in%20India%20from%202013%20to%202016%3A%20a%20systematic%20analysis&author=D.%20Hariharana&author=MK.%20Dasb&author=DS.%20Sheparda&author=NK.%20Arorab&journal=Int.%20J.%20Infect.%20Dis.&volume=84S&pages=S68-S73&publication_year=2019)

10. Harrington, L.C., et al.: Analysis of survival of young and old Aedes aegypti (Diptera: Culicidae) from Puerto Rico and Thailand. J. Med. Entomol. **38**, 537–547 (2001)
CrossRef (https://doi.org/10.1603/0022-2585-38.4.537)
Google Scholar (http://scholar.google.com/scholar_lookup?title=Analysis%20of%20survival%20of%20young%20and%20old%20Aedes%20aegypti%20%28Diptera%3A%20Culicidae%29%20from%20Puerto%20Rico%20and%20Thailand&author=LC.%20Harrington&journal=J.%20Med.%20Entomol.&volume=38&pages=537-547&publication_year=2001)

11. Hung, T.M., et al.: The estimates of the health and economic burden of dengue in Vietnam. Trends Parasitol. **34**(10), 904–918 (2018)
CrossRef (https://doi.org/10.1016/j.pt.2018.07.007)
Google Scholar (http://scholar.google.com/scholar_lookup?title=The%20estimates%20of%20the%20health%20and%20economic%20burden%20of%20dengue%20in%20Vietnam&author=TM.%20Hung&journal=Trends%20Parasitol.&volume=34&issue=10&pages=904-918&publication_year=2018)

12. INE. Statistics Portugal. http://censos.ine.pt (http://censos.ine.pt). Accessed 5 Apr 2020

13. Laserna, A., Barahona-Correa, J., Baquero, L., Castañeda-Cardona, C., Rosselli, D.: Economic impact of dengue fever in Latin America and the Caribbean: a systematic review. Rev. Panam Salud Publica **42**(e111) (2018)
Google Scholar (https://scholar.google.com/scholar?q=Laserna%2C%20A.%2C%20Barahona-Correa%2C%20J.%2C%20Baquero%2C%20L.%2C%20Casta%C3%B1eda-Cardona%2C%20C.%2C%20Rosselli%2C%20D.%3A%20Economic%20impact%20of%20dengue%20fever%20in%20Latin%20America%20and%20the%20Caribbean%3A%20a%20systematic%20review.%20Rev.%20Panam%20Salud%20Publica%2042%28e111%29%20%282018%29)

14. Lee, J.S., et al.: A multi-country study of the economic burden of dengue fever based on patient-specific field surveys in Burkina Faso, Kenya, and Cambodia. PLoS Negl. Trop. Dis. **13**(2), e0007164 (2019)
CrossRef (https://doi.org/10.1371/journal.pntd.0007164)
Google Scholar (http://scholar.google.com/scholar_lookup?title=A%20multi-country%20study%20of%20the%20economic%20burden%20of%20dengue%20fever%20based%20on%20patient-specific%20field%20surveys%20in%20Burkina%20Faso%2C%20Kenya%2C%20and%20Cambodia&author=JS.%20Lee&journal=PLoS%20Negl.%20Trop.%20Dis.&volume=13&issue=2&pages=e0007164&publication_year=2019)

15. Lenhart, C.J., Workman, J.T.: Optimal Control Applied to Biological Models. Chapman & Hall/CRC, Boca Raton (2017)

zbMATH (http://www.emis.de/MATH-item?1291.92010)
Google Scholar (http://scholar.google.com/scholar_lookup?title=Optimal%20Control%20Applied%20to%20Biological%20Models&author=CJ.%20Lenhart&author=JT.%20Workman&publication_year=2017)

16. Maciel-de-Freitas, R., Marques, W.A., Peres, R.C., Cunha, S.P., Lourenço-de-Oliveira, R.: Variation in Aedes aegypti (Diptera: Culicidae) container productivity in a slum and a suburban district of Rio de Janeiro during dry and wet seasons. Mem. Inst. Oswaldo Cruz **102**, 489–496 (2007)
CrossRef (https://doi.org/10.1590/S0074-02762007005000056)
Google Scholar (http://scholar.google.com/scholar_lookup?title=Variation%20in%20Aedes%20aegypti%20%28Diptera%3A%20Culicidae%29%20container%20productivity%20in%20a%20slum%20and%20a%20suburban%20district%20of%20Rio%20de%20Janeiro%20during%20dry%20and%20wet%20seasons&author=R.%20Maciel-de-Freitas&author=WA.%20Marques&author=RC.%20Peres&author=SP.%20Cunha&author=R.%20Louren%C3%A7o-de-Oliveira&journal=Mem.%20Inst.%20Oswaldo%20Cruz&volume=102&pages=489-496&publication_year=2007)

17. Pontryagin, L.S., Boltyanskii, V.G., Gamkrelidze, R.V., Mishechenko, E.F.: The Mathematical Theory of Optimal Processes VIII + 360. Wiley, New York/London (1962)
Google Scholar (http://scholar.google.com/scholar_lookup?title=The%20Mathematical%20Theory%20of%20Optimal%20Processes%20VIII%20%2B%20360&author=LS.%20Pontryagin&author=VG.%20Boltyanskii&author=RV.%20Gamkrelidze&author=EF.%20Mishechenko&publication_year=1962)

18. Public Health Agency of Canada: Statement on Personal Protective Measures to Prevent Arthropod Bites. Canada Communicable Disease Report **38** (2012)
Google Scholar (https://scholar.google.com/scholar?q=Public%20Health%20Agency%20of%20Canada%3A%20Statement%20on%20Personal%20Protective%20Measures%20to%20Prevent%20Arthropod%20Bites.%20Canada%20Communicable%20Disease%20Report%2038%20%282012%29)

19. Pulkki-Brännström, A.M., Wolff, C., Brännström, N., Skordis-Worrall, J.: Cost and cost effectiveness of long-lasting insecticide-treated bed nets - a model-based analysis. Cost Effectiveness Resour. Allocat. **10**(5), 1–13 (2012)
Google Scholar (http://scholar.google.com/scholar_lookup?title=Cost%20and%20cost%20effectiveness%20of%20long-lasting%20insecticide-treated%20bed%20nets%20-%20a%20model-based%20analysis&author=AM.%20Pulkki-Br%C3%A4nnstr%C3%B6m&author=C.%20Wolff&author=N.%20Br%C3%A4nnstr%C3%B6m&author=J.%20Skordis-Worrall&journal=Cost%20Effectiveness%20Resour.%20Allocat.&volume=10&issue=5&pages=1-13&publication_year=2012)

20. Rocha, F.P., Rodrigues, H.S., Monteiro, M.T.T., Torres, D.F.M.: Coexistence of two dengue virus serotypes and forecasting for Madeira Island. Oper. Res. Health Care **7**, 122–131 (2015)
CrossRef (https://doi.org/10.1016/j.orhc.2015.07.003)
Google Scholar (http://scholar.google.com/scholar_lookup?title=Coexistence%20of%20two%20dengue%20virus%20serotypes%20and%2

0forecasting%20for%20Madeira%20Island&author=FP.%20Rocha&author=HS.%20Rodrigues&author=MTT.%20Monteiro&author=DFM.%20Torres&journal=Oper.%20Res.%20Health%20Care&volume=7&pages=122-131&publication_year=2015)

21. Rodrigues, H.S., Monteiro, M.T.T., Torres, D.F.M., Silva, A.C., Sousa, C., Conceição, C.: Dengue in madeira island. In: Bourguignon, J.-P., Jeltsch, R., Pinto, A.A., Viana, M. (eds.) Dynamics, Games and Science. CSMS, vol. 1, pp. 593–605. Springer, Cham (2015). https://doi.org/10.1007/978-3-319-16118-1_32 (https://doi.org/10.1007/978-3-319-16118-1_32)
CrossRef (https://doi.org/10.1007/978-3-319-16118-1_32)
Google Scholar (http://scholar.google.com/scholar_lookup?title=Dengue%20in%20madeira%20island&author=HS.%20Rodrigues&author=MTT.%20Monteiro&author=DFM.%20Torres&author=AC.%20Silva&author=C.%20Sousa&author=C.%20Concei%C3%A7%C3%A3o&pages=593-605&publication_year=2015)

22. Rodrigues, H.S., Monteiro, M.T.T., Torres, D.F.M., Zinober, A.: Dengue disease, basic reproduction number and control. Int. J. Comput. Math. **89**(3), 334–346 (2012)
MathSciNet (http://www.ams.org/mathscinet-getitem?mr=2878568)
CrossRef (https://doi.org/10.1080/00207160.2011.554540)
Google Scholar (http://scholar.google.com/scholar_lookup?title=Dengue%20disease%2C%20basic%20reproduction%20number%20and%20control&author=HS.%20Rodrigues&author=MTT.%20Monteiro&author=DFM.%20Torres&author=A.%20Zinober&journal=Int.%20J.%20Comput.%20Math.&volume=89&issue=3&pages=334-346&publication_year=2012)

23. Shepard, D., Undurraga, E.A., Halasa, Y., Stanaway, J.D.: The global economic burden of dengue: a systematic analysis. Lancet - Infect. Dis. **16**(8), 935–941 (2016)
CrossRef (https://doi.org/10.1016/S1473-3099(16)00146-8)
Google Scholar (http://scholar.google.com/scholar_lookup?title=The%20global%20economic%20burden%20of%20dengue%3A%20a%20systematic%20analysis&author=D.%20Shepard&author=EA.%20Undurraga&author=Y.%20Halasa&author=JD.%20Stanaway&journal=Lancet%20-%20Infect.%20Dis.&volume=16&issue=8&pages=935-941&publication_year=2016)

24. Sher, C.Y., Wong, H.T., Lin, Y.C.: The impact of dengue on economic growth: the case of Southern Taiwan. Int. J. Environ. Res. Public Health **17**(3), 750 (2020)
CrossRef (https://doi.org/10.3390/ijerph17030750)
Google Scholar (http://scholar.google.com/scholar_lookup?title=The%20impact%20of%20dengue%20on%20economic%20growth%3A%20the%20case%20of%20Southern%20Taiwan&author=CY.%20Sher&author=HT.%20Wong&author=YC.%20Lin&journal=Int.%20J.%20Environ.%20Res.%20Public%20Health&volume=17&issue=3&pages=750&publication_year=2020)

25. Stanaway, J.D., et al.: The global burden of dengue: an analysis from the global burden of disease study 2013. Lancet Infect. Dis. **16**(6), 712–23 (2016)
CrossRef (https://doi.org/10.1016/S1473-3099(16)00026-8)
Google Scholar (http://scholar.google.com/scholar_lookup?title=The%20global%20burden%20of%20dengue%3A%20an%20analysis%20from%20the%20global%20burden%20of%20disease%20study%202013&autho

r=JD.%20Stanaway&journal=Lancet%20Infect.%20Dis.&volume=16&issue=6&pages=712-23&publication_year=2016)

26. Suaya, J.A., et al.: Cost of dengue cases in eight countries in the Americas and Asia: a prospective study. Am. J. Trop. Med. Hyg. **80**, 846–855 (2009)
CrossRef (https://doi.org/10.4269/ajtmh.2009.80.846)
Google Scholar (http://scholar.google.com/scholar_lookup?title=Cost%20of%20dengue%20cases%20in%20eight%20countries%20in%20the%20Americas%20and%20Asia%3A%20a%20prospective%20study&author=JA.%20Suaya&journal=Am.%20J.%20Trop.%20Med.%20Hyg.&volume=80&pages=846-855&publication_year=2009)

27. World Health Organization: Managing regional public goods for health: Community-based dengue vector control. Asian Development Bank and World Health Organization, Philippines (2013)
Google Scholar (https://scholar.google.com/scholar?q=World%20Health%20Organization%3A%20Managing%20regional%20public%20goods%20for%20health%3A%20Community-based%20dengue%20vector%20control.%20Asian%20Development%20Bank%20and%20World%20Health%20Organization%2C%20Philippines%20%282013%29)

28. World Health Organization: A toolkit for national dengue burden estimation. WHO, Geneva (2018)
Google Scholar (https://scholar.google.com/scholar?q=World%20Health%20Organization%3A%20A%20toolkit%20for%20national%20dengue%20burden%20estimation.%20WHO%2C%20Geneva%20%282018%29)

Copyright information

About this paper

Cite this paper as:

Brito da Cruz A.M.C., Rodrigues H.S. (2021) Economic Burden of Personal Protective Strategies for Dengue Disease: an Optimal Control Approach. In: Pereira A.I. et al. (eds) Optimization, Learning Algorithms and Applications. OL2A 2021. Communications in Computer and Information Science, vol 1488. Springer, Cham. https://doi.org/10.1007/978-3-030-91885-9_23

- First Online 01 January 2022
- DOI https://doi.org/10.1007/978-3-030-91885-9_23
- Publisher Name Springer, Cham
- Print ISBN 978-3-030-91884-2
- Online ISBN 978-3-030-91885-9
- eBook Packages Computer Science Computer Science (R0)

- Reprints and Permissions

Personalised recommendations

Economic burden of personal protective strategies for dengue disease: an optimal control approach *

Artur M. C. Brito da Cruz[1,3][0000−0001−6136−587X] and Helena Sofia Rodrigues[2,3][0000−0002−6319−7782]

[1] Escola Superior de Tecnologia de Setúbal, Instituto Politécnico de Setúbal, Portugal
[2] Escola Superior de Ciências Empresariais, Instituto Politécnico de Viana do Castelo, Portugal
[3] CIDMA - Centro de Investigação e Desenvolvimento em Matemática e Aplicações, Departamento de Matemática, Universidade de Aveiro, Portugal
artur.cruz@estsetubal.ips.pt, sofiarodrigues@esce.ipvc.pt

Abstract. Dengue fever is a vector-borne disease that is widely spread. It has a vast impact on the economy of countries, especially where the disease is endemic. The associated costs with the disease comprise prevention and treatment. This study focus on the impact of adopting individual behaviors to reduce mosquito bites - avoiding the disease's transmission - and their associated costs. An epidemiological model is presented with human and mosquito compartments, modeling the interaction of dengue disease. The model assumed some self-protection measures, namely the use of repellent in human skin, wear treated clothes with repellent, and sleep with treated bed nets. The household costs for these protections are taking into account to study their use. We conclude that personal protection could have an impact on the reduction of the infected individuals and the outbreak duration. The costs associated with the personal protection could represent a burden to the household budget, and its purchase could influence the shape of the infected's curve.

Keywords: dengue · economic burden · personal protection · household costs · optimal control

1 Introduction

Dengue is a mosquito-borne disease dispersed almost all over the world. The infection occurs when a female Aedes mosquito bites an infected person and then bites another healthy individual to complete its feed [10].

According to World Health Organization (WHO) [27], each year, there are about 50 million to 100 million cases of dengue fever and 500,000 cases of severe dengue, resulting in hundreds of thousands of hospitalizations and over 20,000 deaths, mostly among children and young adults.

Several factors contribute to this public health problem, such as uncontrolled urbanization and increasing population growth. Problems like the increased use of non-biodegradable packaging coupled with nonexistent or ineffective trash collection services, or the growing up number of travel by airplane, allowing the constant exchange of dengue viruses between countries, reflect such factors. Besides, the financial and human resources are limited, leading to programs that emphasize emergency control in response to epidemics rather than on integrated vector management related to prevention [27].

These days, dengue is one of the most important vector-borne diseases and, globally, has heavy repercussions in morbidity and economic impact [1, 28].

1.1 Dengue economic burden

Stanaway *et al.* [25] estimated dengue mortality, incidence, and burden for the Global Burden of Disease Study. In 2013, there were almost 60 million symptomatic dengue infections per year, resulting in about 10 000 deaths; besides, the number of symptomatic dengue infections more than doubled every ten years. Moreover, Shepard *et al.* [23] estimated a total annual global cost of dengue illness of US$8.9 billion, with a distribution of dengue cases of 18% admitted to hospital, 48% ambulatory, and 34% non-medical.

Dengue cases have twofold costs, namely prevention and treatment. The increasing of dengue cases leads to the rise of health expenditures, such as outpatient, hospitalization, and drug administration called direct costs. At the same time, there are indirect costs for the economic operation, such as loss of productivity, a decrease in tourism, a reduction in foreign investment flows. Most of the countries only bet on prevention programs to control the outbreaks. They focus on the surveillance program, with ovitraps or advertising campaigns regarding decrease the breeding sites of the mosquito.

* Supported by FCT - Fundação para a Ciência e a Tecnologia

1.2 Personal Protective Measures (PPM)

Another perspective on dengue prevention is related to household prevention, where the individual has a central role in self-protection. PPM could be physical (e.g., bed nets or clothing) or chemical barriers (e.g., skin repellents).

Mosquito nets are helpful in temporary camps or in houses near biting insect breeding areas. Care is needed not to leave exposed parts of the body in contact with the net, as mosquitoes bite through the net. However, insecticide-treated mosquito nets have limited utility in dengue control programs, since the vector species bite during the day, but treated nets can be effectively utilized to protect infants and night workers who sleep by day [18].

For particular risk areas or occupations, the protective clothing should be impregnated with allowed insecticides and used during biting insect risk periods.

Repellents with the chemical diethyl-toluamide (DEET) give good protection. Nevertheless, repellents should act as a supplementary to protective clothing.

The population also has personal expenses to prevent mosquito bites. There are on the market cans of repellent to apply on the body, clothing already impregnated with insect repellent, and mosquito bed nets to protect individuals when they are sleeping. All of these items have costs and are considered the household cost for dengue.

The number of research papers studying the dengue impact dengue on the country's economy is considerable [9, 11, 13, 23, 24, 26]. However, there is a lack of research related to household expenditures, namely what each individual could spend to protect themselves and their family from the mosquito. There is some work available about insecticide bed nets [19] or house spraying operations [8], but there is a lack of studies using these three PPM in the scientific literature.

Each person has to make decisions related to spending money for its protection or risking catching the disease.

This cost assessment can provide an insight to policy-makers about the economic impact of dengue infection to guide and prioritize control strategies. Reducing the price or attribute subsidies for some personal protection items could lead to an increase in the consumption of these items, and therefore, to prevent mosquito bites and the disease.

This paper studies the influence of the price of personal protection to prevent dengue disease from the individual perspective. Section 2 introduces the optimal control problem, the parameter, and the variables that composed the epidemiological model. Section 3 analyzes the numerical results, and Section 4 presents the conclusions of the work.

2 The epidemiological model

2.1 Dengue epidemiological model

This research is based on the model proposed by Rodrigues *et al.* [21], where it is studied the human and mosquito population through a mutually exclusive compartmental model. The human population is divided in the classic SIR-type epidemiological framework (Susceptible – Infected – Recovered), while the mosquito population only has two components SI (Susceptible - Infected). Some assumptions are assumed: both (humans and mosquitoes) are born susceptibles; there is homogeneity between host and vectors; the human population is constant ($N = S + I + R$), disregarding migrations processes; and seasonality was not considered, which could influence the mosquito population.

The epidemic model for dengue transmission is given by the following systems of ordinary differential equations for human and mosquito populations, respectively.

$$\begin{cases} \dfrac{dS(t)}{dt} = \mu_h N_h - \left(B\beta_{mh}\dfrac{I_m(t)}{N_h} + \mu_h\right) S(t) \\ \dfrac{dI(t)}{dt} = B\beta_{mh}\dfrac{I_m(t)}{N_h} S(t) - (\eta_h + \mu_h)\, I(t) \\ \dfrac{dR(t)}{dt} = \eta_h I(t) - \mu_h R(t) \end{cases} \tag{1}$$

$$\begin{cases} \dfrac{dS_m(t)}{dt} = \mu_m N_m - \left(\dfrac{B\beta_{hm} I(t)}{N_h} + \mu_m\right) S_m(t) \\ \dfrac{dI_m(t)}{dt} = B\beta_{hm}\dfrac{I(t)}{N_h} S_m(t) - \mu_m I_m(t) \end{cases} \tag{2}$$

As expected, these systems depict the interactions of the disease between humans to mosquitoes and vice-versa. Parameters of the model are presented in Table 1.

Table 1: Parameters of the epidemiological model

Parameter	Description	Range	Used values	Source
N_h	Human population		112000	[12]
$\frac{1}{\mu_h}$	Average lifespan of humans (in days)		79×365	[12]
B	Average number of bites on an unprotected person (per day)		$\frac{1}{3}$	[20, 21]
β_{mh}	Transmission probability from I_m (per bite)	$[0.25, 0.33]$	0.25	[6]
$\frac{1}{\eta_h}$	Average infection period on humans (per day)	$[4, 15]$	7	[4]
$\frac{1}{\mu_m}$	Average lifespan of adult mosquitoes (in days)	$[8, 45]$	15	[7, 10, 16]
N_m	Mosquito population		$6 \times N_h$	[22]
β_{hm}	Transmission probability from I_h (per bite)	$[0.25, 0.33]$	0.25	[6]

This model does not incorporate any PPM. Therefore we need to add another compartment to the human population: the Protected (P) compartment. It comprises humans that are using personal protection, and therefore they cannot be bitten by mosquitoes and getting infected.

It is introduced a control variable $u(\cdot)$ in (1), which represents the effort of taking PPM. Additionally, a new parameter is required, ρ, depicting the protection duration per day. Depending on the PPM used, this value is adequate for the individual protection capacity. To reduce computational errors, it was normalized the differential equations, meaning that the proportions of each compartment of individuals in the population were considered, namely

$$s = \frac{S}{N_h}, \quad p = \frac{P}{N_h}, \quad i = \frac{I}{N_h}, \quad r = \frac{R}{N_h}$$

and

$$s_m = \frac{S_m}{N_m}, \quad i_m = \frac{I_m}{N_m}$$

The model with control is defined by:

$$\begin{cases} \frac{ds(t)}{dt} = \mu_h - \left(6B\beta_{mh} i_m(t) + u(t) + \mu_h\right) s(t) + (1-\rho)p(t) \\ \frac{dp(t)}{dt} = u(t)s(t) - \left((1-\rho) + \mu_h\right) p(t) \\ \frac{di(t)}{dt} = 6B\beta_{mh} i_m(t)s(t) - \left(\eta_h + \mu_h\right) i(t) \\ \frac{dr(t)}{dt} = \eta_h i(t) - \mu_h r(t) \end{cases} \tag{3}$$

and

$$\begin{cases} \frac{ds_m(t)}{dt} = \mu_m - \left(B\beta_{hm} i(t) + \mu_m\right) s_m(t) \\ \frac{di_m(t)}{dt} = B\beta_{hm} i(t)s_m(t) - \mu_m i_m(t) \end{cases} \tag{4}$$

This set of equations is subject to the initial equations ([21]):

$$s(0) = \frac{11191}{N_h}, p(0) = 0, i(0) = \frac{9}{N_h}, r(0) = 0, s_m(0) = \frac{66200}{N_m}, i_m(0) = \frac{1000}{N_m}. \qquad (5)$$

The mathematical model is represented by the epidemiological scheme in Figure 1.

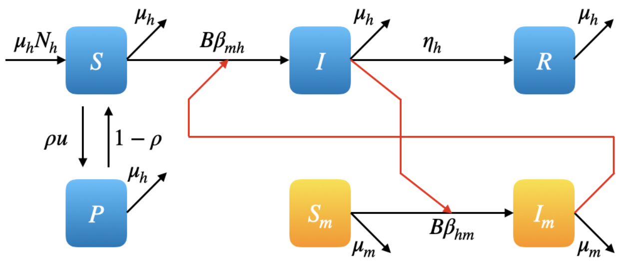


Fig. 1: Flow Diagram of Dengue model with personal protection strategies

Due to the impossibility of educating everyone to use PPM, namely because of budget constraints, time restrictions, or even the low individual willingness to using PPM, it is considered that the control $u(\cdot)$ is bounded between 0 and $u_{max} = 0.7$.

2.2 Optimal control problem

In this section, an optimal control problem is proposed that portrays the costs associated with PPM and the restrictions of the epidemy.

The objective functional is given by

$$J(u(\cdot)) = R(T) + \int_0^T \gamma u^2(t)dt \qquad (6)$$

where γ is a constant that represents the cost of taking personal prevention measures per day and person. At the same time, it is relevant that this functional also has a payoff term: the number of humans recovered by disease at the final time, $R(T)$. It is expected that the outbreak dies out, and therefore, the total of recover individuals gives the cumulative number of persons infected by the disease. We want to minimize the total number of infected persons, and therefore recovered persons at the final time and the expenses associated with buying protective measures.

Along time, we want to find the optimal value u^* of the control u, such that the associated state trajectories $S^*, P^*, I^*, R^*, S_m^*, I_m^*$ are solutions of the equations (3) and (4) with the following initial conditions:

$$s(0) \geqslant 0, \quad p(0) \geqslant 0, \quad i(0) \geqslant 0, \quad r(0) \geqslant 0, \quad s_m(0) \geqslant 0, \quad i_m(0) \geqslant 0. \qquad (7)$$

The set of admissible controls is

$$\Omega = \{u(\cdot) \in L^\infty [0,T] : 0 \leqslant u(\cdot) < \text{umax}, \forall t \in [0,T]\}.$$

The optimal control consists of finding $(s^*(\cdot), p^*(\cdot), i^*(\cdot), r^*(\cdot), s_m^*(\cdot), i_m^*(\cdot))$ associated with an admissible control $u^*(\cdot) \in \Omega$ on the time interval $[0,T]$ that minimizes the objective functional.

Note that the cost function is L^2 and the integrand function is convex with respect to the function u. Furthermore, the control systems are Lipschitz with respect to the state variables and, therefore, exists an optimal control ([3]).

The Hamiltonian function is

$$
\begin{aligned}
H =& H\left(s(t), p(t), i(t), r(t), s_m(t), i_m(t), \Lambda, u(t)\right) = \gamma u^2(t) \\
&+ \lambda_1\left(\mu_h - \left(6B\beta_{mh} i_m(t) + u(t) + \mu_h\right)s(t) + (1-\rho)p(t)\right) \\
&+ \lambda_2\left(u(t)s(t) - \left((1-\rho) + \mu_h\right)p(t)\right) \\
&+ \lambda_3\left(6B\beta_{mh} i_m(t)s(t) - \left(\eta_h + \mu_h\right)i(t)\right) \\
&+ \lambda_4\left(\eta_h i(t) - \mu_h r(t)\right) \\
&+ \lambda_5\left(\mu_m - \left(B\beta_{hm} i(t) + \mu_m\right)s_m(t)\right) \\
&+ \lambda_6\left(B\beta_{hm} i(t) s_m(t) - \mu_m i_m(t)\right)
\end{aligned}
$$

Pontryagin's Maximum Principle [17] states that if $u^*(\cdot)$ is optimal control for the equations (3)-(6) with fixed final time, then there exists a nontrivial absolutely continuous mapping, the adjoint vector:

$$
\Lambda : [0,T] \to \mathbb{R}^6,\ \ \Lambda(t) = \left(\lambda_1(t), \lambda_2(t), \lambda_3(t), \lambda_4(t), \lambda_5(t), \lambda_6(t)\right)
$$

such that

$$
s' = \frac{\partial H}{\partial \lambda_1}, \quad p' = \frac{\partial H}{\partial \lambda_2}, \quad i' = \frac{\partial H}{\partial \lambda_3}, \quad r' = \frac{\partial H}{\partial \lambda_4}, \quad s'_m = \frac{\partial H}{\partial \lambda_5} \text{ and } i'_m = \frac{\partial H}{\partial \lambda_6},
$$

and where the optimality condition

$$
\begin{aligned}
&H\left(s^*(t), p^*(t), i^*(t), r^*(t), s^*_m(t), i^*_m(t), \Lambda(t), u^*(t)\right) = \\
&= \min_{0 \leqslant u < u_{max}} H\left(s^*(t), p^*(t), i^*(t), r^*(t), s^*_m(t), i^*_m(t), \Lambda(t), u(t)\right)
\end{aligned}
$$

and the transversality conditions

$$
\lambda_i(T) = 0, \qquad i = 1,2,3,5,6 \quad \textit{and} \quad \lambda_4(T) = 1 \tag{8}
$$

hold almost everywhere in $[0,T]$.

The following theorem follows directly from applying the Pontryagin's maximum principle to the optimal control problem.

Theorem 1. *The optimal control problem with fixed final time T defined by the equations (3)-(6) has a unique solution $(s^*(t), p^*(t), i^*(t), r^*(t), s^*_m(t), i^*_m(t))$ associated with the optimal control $u^*(\cdots)$ on $[0,T]$ given by*

$$
u^*(t) = \max\left\{0, \min\left\{\frac{\left(\lambda_1(t) - \lambda_2(t)\right)s^*(t)}{2\gamma}, u_{max}\right\}\right\} \tag{9}
$$

with the adjoint function satisfying

$$
\begin{cases}
\lambda'_1(t) = \lambda_1\left(6B\beta_{mh} i^*_m(t) + u^*(t) + \mu_h\right) - \lambda_2 u^*(t) - \lambda_3 6B\beta_{mh} i^*_m(t) \\
\lambda'_2(t) = -\lambda_1(1-\rho) + \lambda_2\left((1-\rho) + \mu_h\right) \\
\lambda'_3(t) = \lambda_3\left(\eta_h + \mu_h\right) - \lambda_4 \eta_h + \left(\lambda_5 - \lambda_6\right)B\beta_{hm} s^*_m(t) \\
\lambda'_4(t) = \lambda_4 \mu_h \\
\lambda'_5(t) = \lambda_5\left(B\beta_{hm} i^*(t) + \mu_m\right) - \lambda_6 B\beta_{hm} i^*(t) \\
\lambda'_6(t) = \left(\lambda_1 - \lambda_3\right)6B\beta_{mh} s^*(t) + \lambda_6 \mu_m
\end{cases} \tag{10}
$$

3 Numerical results

This section presents the results of the numerical implementation of control strategies for PPM for dengue disease.

For the problem resolution, the time frame considered was one year, and the parameters used are available on Table 1.

To obtain the computational results, Theorem 1 was implemented numerically on MATLAB version R2017b and the extremal found, u^*, was evaluated using a forward-backward fourth-order Runge–Kutta method with a variable time step for efficient computation (see [15] for more details). For the differential equations related to the state variables, (3)-(4) it was performed a forward method using the initial conditions (5). For the differential equations related to adjoint variables, it was applied a backward system using the transversality conditions (8).

Figure 2 shows the evolution of the human state variables during the whole year, without any control. This analysis is a meaningful kickoff point to make a fair comparison with the application of the PPM. It should also be mentioned that this model does not take into account deaths by dengue, because in the considered region of the study [21], fortunately, nobody died, and there were no cases of hemorrhagic fever.

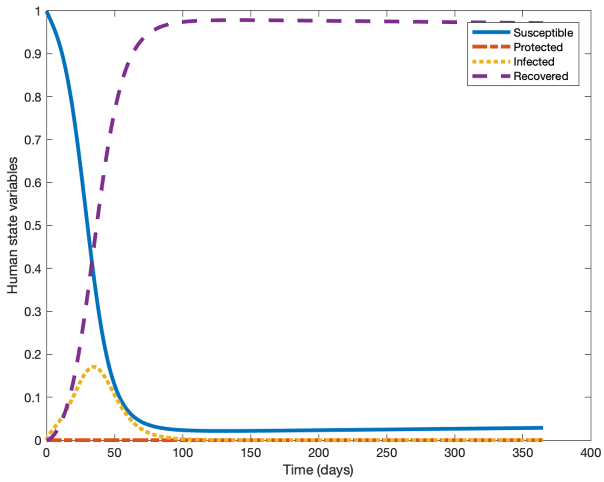


Fig. 2: Evolution of human state variables when human population did not take any protective measures

For this research, three protective measures were considered: insect repellent, bed nets, and clothes impregnated with insect repellent. It was obtained the average price of each product on the market as well as how long each product stays active.

The following simulations are divided into two subsections: the first one, using only one PPM, and the second one, where several PPM are combined. Each PPM has two factors associated: cost and durability. In our model, the parameter γ is the cost that each individual spends to protect themself during the whole year, and the parameter ρ determines how long the protection stays active. The individual is responsible for deciding the best strategy and how much he/she will spend on protective measures. Both constants are listed in Table 2. For example, the cost of a spray can of insect repellent is 10€, and it only lasts a month, the reason why $\gamma = \frac{10\times 12}{365\times N_h}$. Furthermore, each application of insect repellent only lasts four hours, hence ρ as the value $\frac{1}{6}$.

Therefore, this analysis is twofold purposes: to understand the impact in the curve of infected individuals when distinct personal protective measures are used; and to find the economic burden of these measures on each person.

Table 2: Parameters associated with the control

	Scenario	Control	Cost (γ)	Protection (ρ)
No control		none	0	0
Single control	A	Skin repellent	$\frac{10\times 12}{365\times N_h}$	$\frac{1}{6}$
	B	Bed net	$\frac{20}{365\times N_h}$	$\frac{1}{3}$
	C	Insecticide-treated clothes	$\frac{30\times 6}{365\times N_h}$	$\frac{1}{2}$
Combined control	D	Skin repellent+Bed net	$\frac{10\times 12+20}{365\times N_h}$	$\frac{1}{2}$
	E	Skin repellent+Insecticide-treated clothes	$\frac{10\times 12+30\times 6}{365\times N_h}$	$\frac{2}{3}$
	F	Bed net+Insecticide-treated clothes	$\frac{20+30\times 6}{365\times N_h}$	$\frac{5}{6}$
	G	All	$\frac{10\times 12+20+30\times 6}{365\times N_h}$	1

3.1 Single control

In this section, it is presented the results relative to the application of one single control. Only one of the protective measures, skin repellent, bed nets, or clothes impregnated with insecticide, is taken and only used once per day.

In scenario A (see Figure 3), the case associated with the use of skin repellent, is the case where more people get infected. About 85% of the population gets infected, and that's probably why, in the single control scenarios, this is the case where the control starts to decrease sooner. A reasonable argument why this happens is because the protective measure is not being very effective. Note that this is the case where people are less protected.

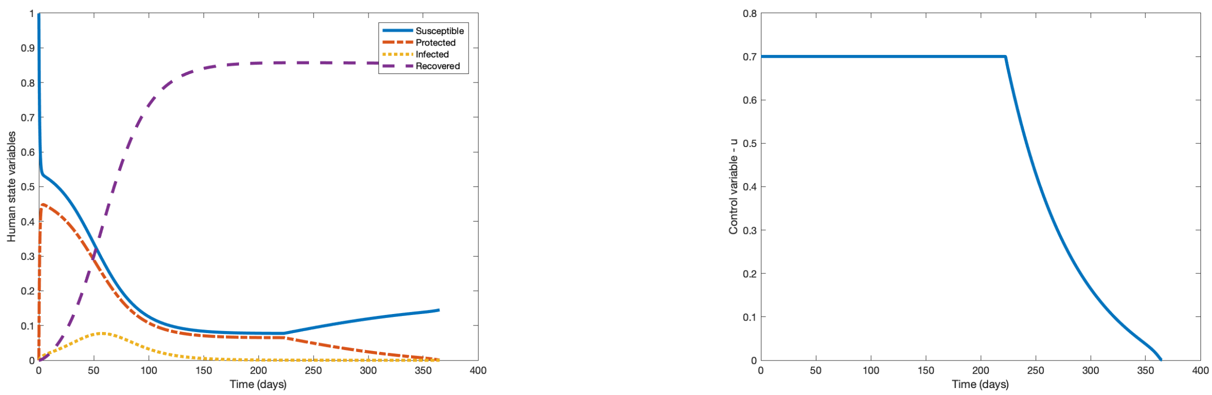


Fig. 3: Scenario A - Control used: skin repellent

Scenarios B (Figure 4) and C (Figure 5) have similar behavior of the control function; however, scenario C is the first case where the number of protected persons is larger than the number of susceptible persons, at least most of the year.

Note that the cost of using treated clothes is much higher than using bed nets. However, there is not much difference between the total number of infected persons using bed nets instead of treated clothes, about 500 more infected persons.

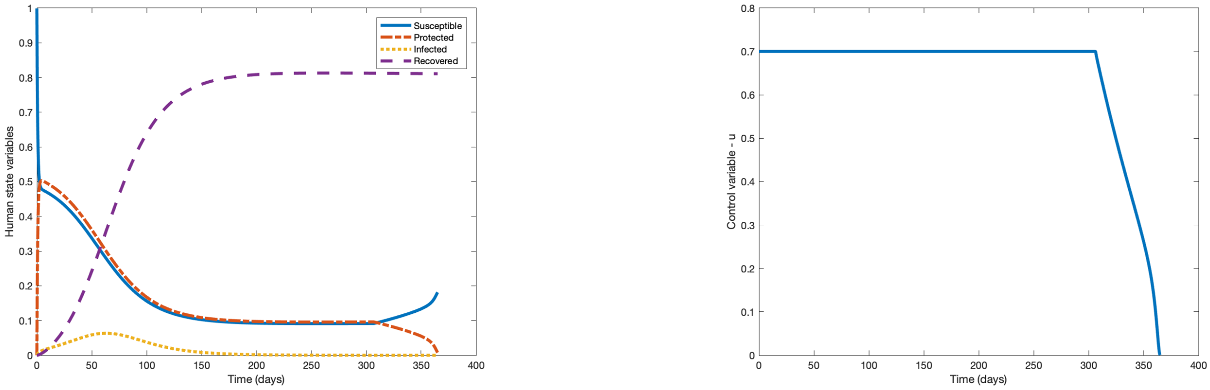


Fig. 4: Scenario B - Control used: bed nets

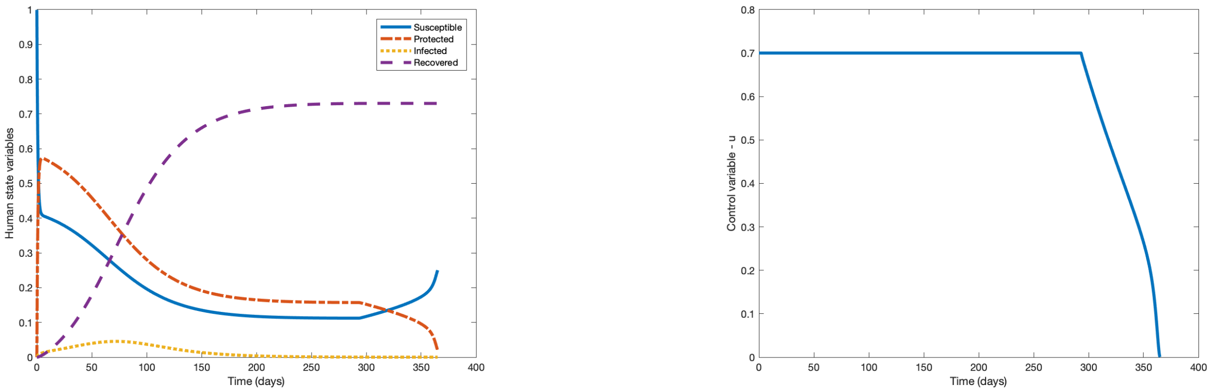


Fig. 5: Scenario C - Control used: insecticide-treated clothes

3.2 Combined control

Another approach to household protection is the combination of more than one protective measure. Wearing or using more personal protections significantly reduces the number of infected persons. The combined use of insect repellent and bed nets, scenario D (Figure 6), have the same value of ρ as scenario C and, therefore, the human state variables and control function of these cases have similar behavior. The big difference between both scenarios, C and D, is the cost of the protections, which will be discussed in the following subsection.

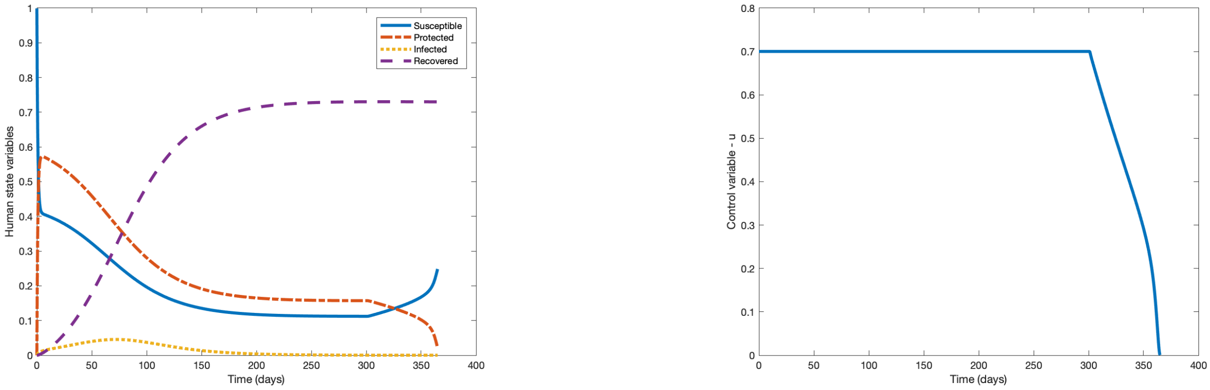


Fig. 6: Scenario D - Combined control (insect repellent and bed nest)

In scenarios E (Figure 7), F (Figure 8), and G (Figure 9), the number of infected people is quite inferior to previous cases. The final number of recovered persons drops down at least to almost half the population. The control function keeps increasing the number of days staying at maximum control until scenario F. This seems to happen because the number of infected persons in this scenario reduces significantly.

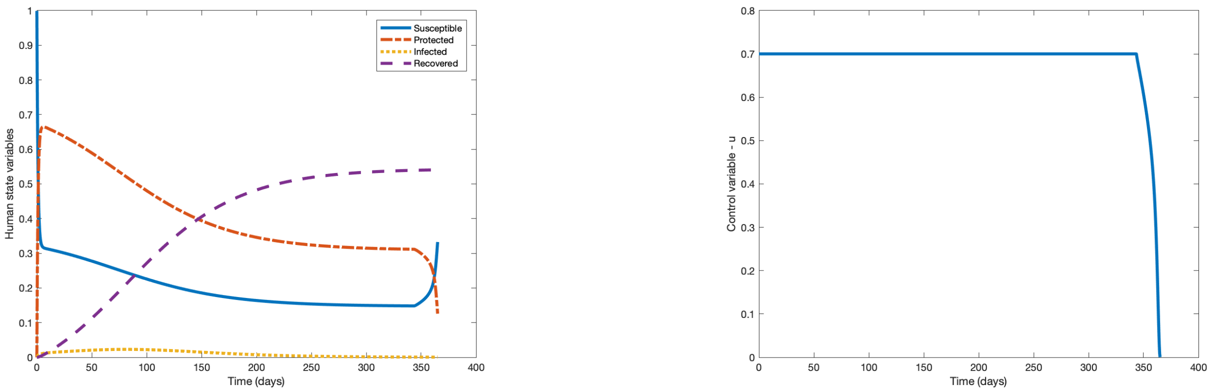


Fig. 7: Scenario E - Combined control (Skin repellent and Insecticide-treated clothes)

In scenario F, a large number of persons have personal protection. The maximum number of infected persons on a day is 99. In this scenario, the human state variables have completely different behavior than the previous scenarios. This amount of protection has an impact on the epidemy.

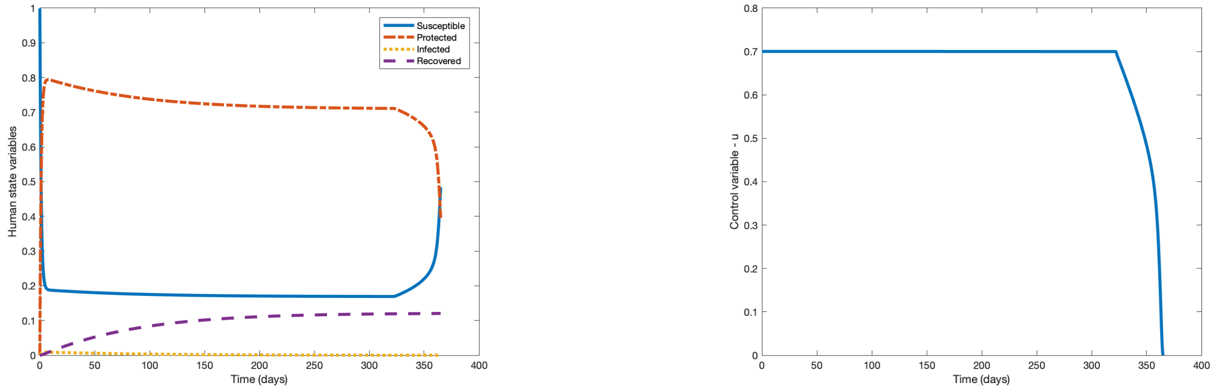


Fig. 8: Scenario F - Combined control (Bed net and Insecticide-treated clothes)

Scenario G is almost utopic since the individual has complete protection every hour of the day. Right from the start, 70% of the population is protected, and in 41 days, there will not be more infections with dengue disease. Overall costs decrease because people do not have to apply personal protections most of the year.

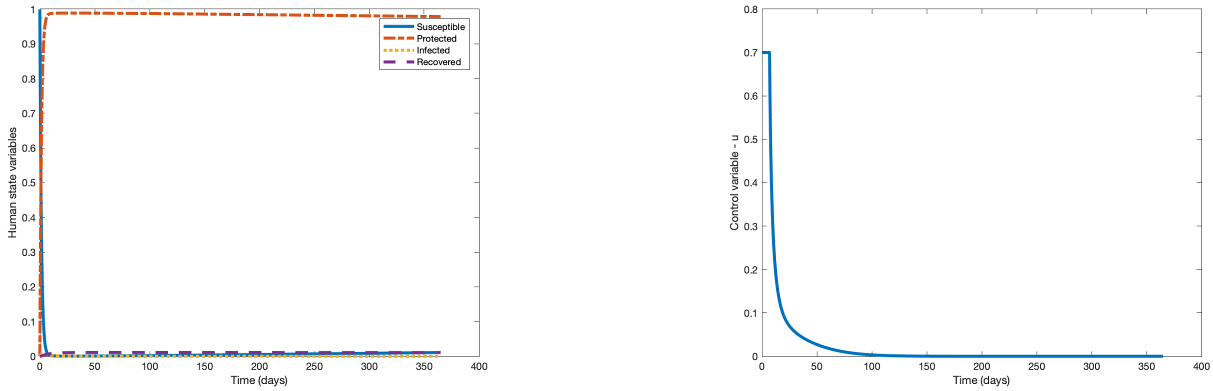


Fig. 9: Scenario G - Combined control (skin repeelent, bed net, insecticide-treated clothes)

3.3 Cost of the control

Control measures associated with personal protection were analyzed, separately and combined, to achieve the best strategy. Table 3 illustrates the differences of all scenarios, and several relevant values were scrutinized to understand the dynamics of human state variables. The peak of the infection, the maximum number of infected persons in a day, and the day when that happens are pointed out to perceive the total number of infected individuals; this information is crucial to prepare in advance human and medical resources for an outbreak. The epidemy's end is considered the day when the number of infected persons is smaller than 9, which corresponds to the initial value of infected persons on these simulations. Finally, the last two columns are concerned with the functional cost. $R(T)$ represents the number of recovered persons on the last day of the year contemplated, also it tells the total number of infected people during the whole year. The cost of personal protection measure stands for the value that each person would have to spend during the whole year.

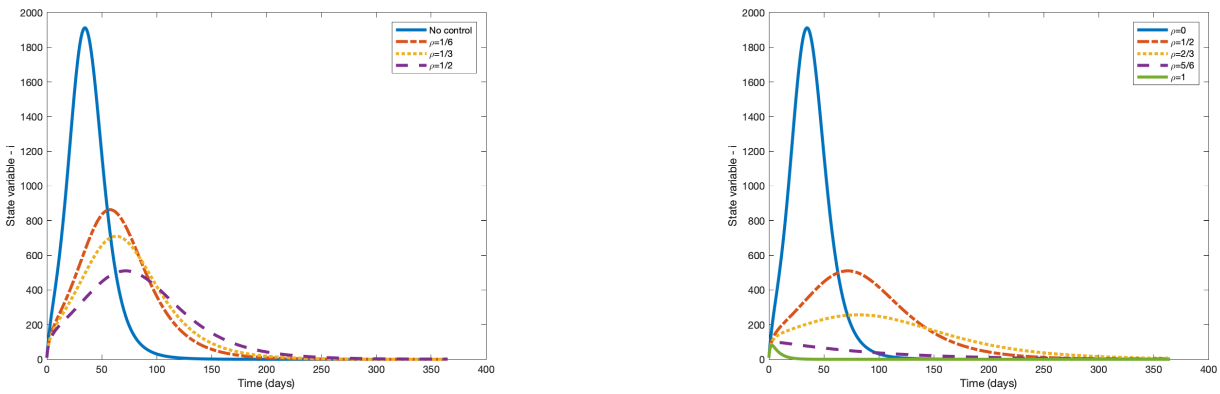
The maximum value of infected people on a single day occurs, as expected, when there are no personal protection measures. The minimum value is 81 where people are fully protected but in scenario F, with $\rho = \frac{5}{6}$, only have a few more infected persons at its peak, 99. Strategies C and D have likely results regarding the peak of the infection and according to the respective figures presented in previous subsections. However, the cost of using only insecticide-treated clothes (scenario C) is 26% higher when compared with the combined control insect repellent and bed net (scenario D).

In Table 3, one can see that with more protection measures, the maximum number of infected people in a single day decreases. However, the day when this peak is achieved is surprising. This peak is reached on the 35th day, where there isn't any control, and it keeps being reached later until scenario E, 81st day. In these scenarios, from no control until scenario E, flattening the curve of infected people makes the duration of the epidemy last longer. Both columns, Epidemy's end and $R(t)$, illustrate this fact. In the last two scenarios, and due to a large number of the population is using protection almost all of the day, the total number of infected people drastically decreases. In these two cases, the human state variables have different behavior from the other scenarios.

Table 3: Parameters associated with the control

Scenario	ρ	Peak of infected persons	Peak's day	Epidemy's end (day)	R(T)	Cost
No control	0	1912	35	120	10878	0
A	$\frac{1}{6}$	863	58	202	9571	62,5
B	$\frac{1}{3}$	710	63	223	9083	13
C	$\frac{1}{2}$	510	72	260	8177	115,7
D	$\frac{1}{2}$	510	72	261	8176	91,3
E	$\frac{2}{3}$	257	81	336	6057	206,1
F	$\frac{5}{6}$	99	6	221	1349	135,3
G	1	81	3	20	120	8,7

Another perspective of the outbreak is to present all curves of infected humans (Figure 10). The adoption of any PPM decreases the peak of the infected, which could influence the medical care of the patients. Higher values of ρ mean less number of infected people. Inversely, the epidemic's end and its peak happen later for higher values of ρ (except the last two cases), which could be explained by the flattening of the curve of infected persons.

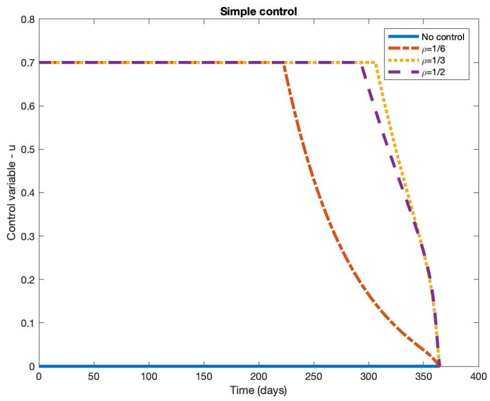


Single control scenarios

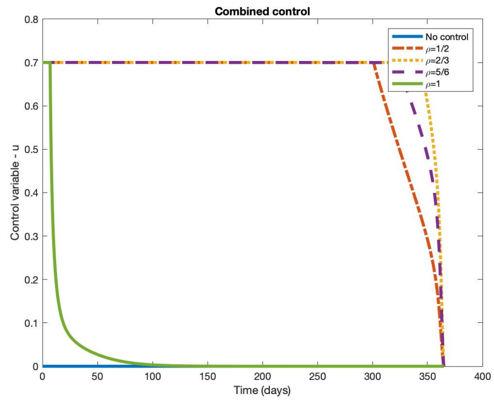
Combined control scenarios

Fig. 10: Infected people - all scenarios

Control functions on all scenarios tend to stay at maximum control value for most of the year at study. However, in scenario A, the control function starts to drop down from the maximum value much sooner than in all other scenarios. A possible explanation seems to be because, on the 200th day, most people already were infected by dengue. Therefore, there is no need for any more protection. Again on scenarios F and G, due to the end of epidemy's is reached sooner, the control function also starts to decrease sooner when comparing it with the remaining scenarios (see Figure 11).



Single control scenarios



Combined control scenarios

Fig. 11: Control variable - all scenarios

Protective measures have varied prices, and the duration that each one lasts is different. Scenarios F and G seem to prove that the use of very efficient protection from the start of the outbreak, ends it sooner. Furthermore, and possibly not expected, each person in these scenarios does not spend as much money as in other cases. For instance, scenario F appears to be a much better solution than scenario E, not only for personal cost but also to fight the disease.

4 Conclusions

Effective dengue prevention requires a coordinated and sustainable approach. This way, it is possible to address environmental, behavioral, and social contexts of disease transmission. Determining household expenditure related to bite prevention is a crucial purpose for acting in advance of an outbreak. With an efficient cost analysis, each individual could make a trade-off decision between the available resources.

This work is the follow up work that the authors started in [2]. In here, the research tried to answer the following question: what is the best strategy to fight dengue disease and, at the same time, spending less money?

The results corroborated that if one person is more protected, then the disease spreads less. Long protection flattens the infected human curve, which is a good perspective from the medical point of view. Hence, the medical staff could have more time to prepare the outbreak response, and the Heath Authorities could acquire more supplies to treat the patients.

However, it was found that does not mean that the person should spend more. As an example, the protection used with skin repellent and bed net has the same impact on the number of infected individuals when compared with the insecticide-treated clothes, but it is much cheaper.

These results also reflect the importance of using personal protective measures for most part of the day. Half or even more of the population will not be infected if at least 16 hours a day a person stays protected.

As future work, it will be interesting to study the economic impact of strategies related to prevention - including self-protect measures - and treatment - that could including costs with drug administration, hospitalization, or even sick days losses, focusing only on the individual perspective. Another perspective to be implemented is to analyze the economic evaluation of prevention. The adoption of some prevention activities, from the individual point of view, could have a profound impact on the government budget allocated to the disease's treatment. Thus could be critical to investigate the financial support of preventive measures.

Acknowledgement

This work is supported by The Center for Research and Development in Mathematics and Applications (CIDMA) through the Portuguese Foundation for Science and Technology (FCT - Fundação para a Ciência e a Tecnologia), references UIDB/04106/2020 and UIDP/04106/2020.

References

1. Bhatt, S., Gething, P.W., Brady, O.J., Messina, J.P., Farlow, A.W., Moyes, C.L,; Drake, J.M., Brownstein, J.S., Hoen, A.G., Sankoh, O., et al.:The global distribution and burden of dengue. Nature **496**, 504–507 (2013)
2. Brito da Cruz, A. M. C., Rodrigues, H. S.: Personal protective strategies for dengue disease: Simulations in two coexisting virus serotypes scenarios. Mathematics and Computers in Simulation **188**, 254-267 (2021)
3. Cesari, L.: Optimization—Theory and Applications. Springer-Verlag, New York, USA, (1983)
4. Chan, M., Johansson, M. A.: The Incubation Periods of Dengue Viruses. PLoS ONE **7**(11), (2012)
5. Demers, J., Bewick, S., Calabrese, J., Fagan, W.F.: Dynamic modelling of personal protection control strategies for vector-borne disease limits the role of diversity amplification. J. R. Soc. Interface **15**, (2018)
6. Focks, D. A., Brenner, R. J., Hayes, J., Daniels, E.: Transmission thresholds for dengue in terms of Aedes aegypti pupae per person with discussion of their utility in source reduction efforts. Am. J. Trop. Med. Hyg. **62**, 11—18 (2000)
7. Focks, D. A., Haile, D.G., Daniels, E., Mount, G A.: Dynamic life table model for Aedes aegypti (Diptera: Culicidae): analysis of the literature and model development. J. Med. Entomol. **30** , 1003—1017 (1993)
8. Goodman, C. A., Mnzava, A. E. P., Dlamini, S. S., Sharp, B. L., Mthembu, D. J., Gumede, J. K.: Comparison of the cost and cost-effectiveness of insecticide-treated bednets and residual house-spraying in KwaZulu-Natal, South Africa. Tropical Medicine and International Health **6**(4), 280–95 (2001)
9. Hariharana, D., Dasb, M.K., Sheparda, D.S., Arorab, N.K.: Economic burden of dengue illness in India from 2013 to 2016: A systematic analysis. International Journal of Infectious Diseases **84S**, S68—S73 (2019)
10. Harrington, L. C., Buonaccorsi, J.P., Edman, J.D., Costero, A., Kittayapong, P., Clark, G. G., Scott, T. W.: Analysis of survival of young and old Aedes aegypti (Diptera: Culicidae) from Puerto Rico and Thailand. Journal of Medical Entomology **38**, 537-–547 (2001)
11. Hung, T.M., Clapham, H.E., Bettis, A.A., Cuong, H.Q., Thwaites, G.E., Wills, B.A., Boni, M.F., Turner, H.C.: The Estimates of the Health and Economic Burden of Dengue in Vietnam. Trends in Parasitology **34**(10), 904–918 (2018)
12. INE. Statistics Portugal, http://censos.ine.pt. Last accessed 5 April 2020.
13. Laserna, A., Barahona-Correa, J., Baquero, L., Castañeda-Cardona, C., Rosselli, D.: Economic impact of dengue fever in Latin America and the Caribbean: a systematic review. Rev Panam Salud Publica **42**(e111), (2018)
14. Lee, J.S., Mogasale, V., Lim, J.K., Ly, S., Lee, K.S., Sorn, S., et al.: A multi-country study of the economic burden of dengue fever based on patient-specific field surveys in Burkina Faso, Kenya, and Cambodia. PLoS Negl Trop Dis **13**(2), (2019)
15. Lenhart,C.J., Workman, J.T.: Optimal control applied to biological models. Chapman & Hall/CRC, Boca Raton, FL, USA, (2017)
16. Maciel-de-Freitas, R., Marques, W.A., Peres, R.C., Cunha, S.P., Lourenço-de-Oliveira, R.: Variation in Aedes aegypti (Diptera: Culicidae) container productivity in a slum and a suburban district of Rio de Janeiro during dry and wet seasons. Mem. Inst. Oswaldo Cruz **102**, 489-–496 (2007)
17. Pontryagin, L. S., Boltyanskii, V. G., Gamkrelidze, R. V., Mishechenko, E. F.: The Mathematical Theory of Optimal Processes VIII + 360. S. John Wiley & Sons, New York/London (1962)
18. Public Health Agency of Canada: Statement on Personal Protective Measures to Prevent Arthropod Bites. Canada Communicable Disease Report **38**, (2012).
19. Pulkki-Brännström, A.M., Wolff, C., Brännström, N., Skordis-Worrall, J.: Cost and cost effectiveness of long-lasting insecticide-treated bed nets - a model-based analysis. Cost Effectiveness and Resource Allocation **10**(5), 1–13 (2012)
20. Rocha, F.P. , Rodrigues, H.S., Monteiro, M.T.T., Torres, D.F.M., Coexistence of two dengue virus serotypes and forecasting for Madeira Island. Operations Research for Health Care **7**, 122–131 (2015)
21. Rodrigues, H. S., Monteiro, M.T., Torres, D.F.M., Silva, A.C., Sousa, C.: Dengue in Madeira Island. Bourguignon, J.P., Jeltsch, R., Pinto, A., Viana, M. (eds.) International Conference and Advanced School Planet Earth, DGS II, CIM Series in Mathematical Sciences, vol 1, pp. 593–605 . Springer, Cham (2015).
22. Rodrigues, H. S., Monteiro, M.T.T., Torres, D.F.M., Zinober, A.: Dengue disease, basic reproduction number and control. Int. J. Comput. Math., **89**(3) 334—346 (2012)

23. Shepard, D., Undurraga, E.A., Halasa, Y., Stanaway, J.D.: The global economic burden of dengue: a systematic analysis. The Lancet - Infectious Diseases, **16**(8), 935-941 (2016)
24. Sher, C.Y., Wong, H.T., Lin, Y.C.: The impact of Dengue on Economic Growth: the case of Southern Taiwan. Int. J. Environ. Res. Public Health **17**(3), 750 (2020)
25. Stanaway, J.D., Shepard, D.S., Undurraga, E.A., Halasa, Y.A., Coffeng, L.E., Brady, O.J., et al.: The global burden of dengue: an analysis from the global burden of disease study 2013. Lancet Infect Dis **16**(6), 712-23. (2016)
26. Suaya, J.A., Shepard, D.S., Siqueira, J.B., Martelli, C.T., Lum, L.C., Tan, L.H., Kongsin, S., Jiamton, S., Garrido, F., Montoya, R., et al.: Cost of dengue cases in eight countries in the Americas and Asia: A prospective study. Am. J. Trop. Med. Hyg **80**, 846-855 (2009)
27. World Health Organization, Managing regional public goods for health: Community-based dengue vector control. Asian Development Bank and World Health Organization, Philippines (2013)
28. World Health Organization, A toolkit for national dengue burden estimation. WHO, Geneva (2018)