Description of model behavior

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# Description of model variables

## Input variables

Table 1: Input parameters varied in the experiments.

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| **Parameters** | **Description** | **Range** |
| Propensity\_value\_adaptation | Likeliness that agents will choose value adaptation to act upon moral problems. | [0-1] |
| Propensity\_value\_dynamism | Likeliness that agents will choose value dynamism to act upon moral problems. | [0-1] |
| Propensity\_innovation | Likeliness that agents will choose innovation to act upon moral problems. | [0-1] |
| Openness\_to\_change | Pace at which values are changed and probability of finding new technologies | [0-100] |
| Value\_memory\_of\_society | Pace at which unaffected values are forgotten | [0-100] |
| frequency\_need\_change | Frequency of change in case needs change over time | [1000-10000] |
| max\_need\_change | Maximum increase or decrease of needs in case needs change over time | [0.5-4] |

## Output variables

Table 2: Output parameters of the model

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| **Output parameters** | **Output parameter name** |
| Number of moral problems that society has discovered throughout the simulation run using their values | ‘number\_of\_moral\_problems\_discovered\_through\_values’ |
| Number of moral problems that society has discovered throughout the simulation run because they exceeded the threshold (moral problems were severe) | ‘number\_of\_moral\_problems\_discovered\_through\_threshold’ |
| Sum of the severity of moral problems encountered throughout the simulation run | ‘total\_severity\_of\_moral\_problems’ |
| Average number of existing perceived moral problems throughout the simulation run | ‘average\_number\_of\_perceived\_moral\_problems’ |
| Average number of existing unperceived moral problems throughout the simulation run | ‘average\_number\_of\_unperceived\_moral\_problems’ |
| Number of moral problems that have emerged throughout the simulation run | ‘number\_of\_moral\_prolbems\_emerged’ |
| Number of moral problems that existed when moral revolutions have occurred. | ‘count\_moral\_problems\_when\_moral\_revolution’ |
| Number of values that existed when moral revolutions have occurred. | ‘count\_values\_when\_moral\_revolution’ |
| Average number of moral problems in the model throughout the simulation run | ‘average\_number\_of\_moral\_problems’ |
| Average number of values in the model throughout the simulation run | ‘average\_number\_of\_values’ |
| Number of moral revolutions that has occurred throughout one simulation run | ‘count\_moral\_revolutions’ |
| Number of lock-in situations that has occurred throughout one simulation run | ‘count\_lock\_in\_situations’ |

# Model conceptualization

A summary of the model conceptualization is provided in this section. The simulation model we have built represents a society where agents address societal needs by using technologies. The usage of these technologies can cause moral problems. If so, agents have the following three options to address moral problems. A first option is to adjust the values of society (*value adaptation*). As a result, the technology that has resulted in moral problems becomes less desirable. A second option is to adjust the values of society, but only temporarily (*value dynamism*). The consequences are the same as for value adaptation, but the values that have been adjusted will return to their initial settings over time. A third option is to create a new technology (*innovation*). If possible, the newly created technology will be in line with current values of the society (assuming agents aim for responsible innovation).

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Figure : Conceptual model

# Effect of model input variables

## Effect of value memory

The variable ‘Value\_memory\_of\_society’ reflects how conservative a society is with regard to the values that it holds. If Value\_memory\_of\_society is set to low, (new) values will be quickly forgotten. As a result, it is likely that the society will not have the right values when encountering new moral problems. It might take more time for society to create new values or technologies in response to these moral problems. If Value\_memory\_of\_society is set to high, the number of technologies that are deemed morally unacceptable is also likely to be higher. Some technologies that are not in line with current might not be used by agents, even though they are not causing moral problems.

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Figure : Effect of the value memory on main output variables

Figure 2 shows the effect of lower and higher value memory on main output variables of the model. As expected, the longer values are remembered, the higher is the average number of values that exist in society. Following the same rationale, a higher value memory should also lead to more technologies (because more values lead to more unacceptable technologies and therefore more innovation). However, this only seems to be the case when the value memory is lower than 20. When higher than 20, the value memory does not seem to have an effect. This is also the case if the number of unacceptable technologies, which shows also increase when the number of values is higher.

This observation is explained by the role of values in the model. When the value memory is higher than 20, values exist sufficiently long in the model in order to have an effect on the identification of new moral problems. Moral problems can be discovered through values (i.e., because society has the adequate values to identify them), or through a threshold (i.e., the moral problem is so large that it eventually becomes perceived by society). As can be seen in Figure 2, moral problems are essentially discovered by means of the threshold when the value memory is lower than 20. When the value memory is higher, values start to have an effect on the model. The number of moral problems discovered through values increases, the severity of moral issues stabilizes and similarly for the number of unacceptable technologies in the model.

## Effect of openness to change

The variable ‘openness\_to\_change’ reflects how open a society is towards new values and new technologies. Agents can react to new moral problems by adjusting their values (value adaptation and value dynamism) and by creating new technologies that do not create the same moral problems (innovation). If openness\_to\_change is set to high, agents will proceed to a stronger incremental change of values when choosing value adaptation and value dynamism. Agents will have a higher chance of creating a suitable new technology when choosing innovation.

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Figure : Effect of openness to change on main output variables.

Figure 3 shows the effect of lower and higher openness to change on main output variables of the model. We observe that a higher openness to change leads to more values, but only when the openness to change is lower than 20. Logically, a higher openness to change leads to more technologies, of which some of them may be unacceptable. Remarkably, openness to change does not seem to largely lead to a lower number of moral problems on average. However, we find that a distinction needs to be made between perceived and unperceived moral problems. The number of perceived moral problem decreases with a higher openness to change, while the number of unperceived moral problems increases slightly.

This observation is explained by the fact that openness to change leads to a higher number of technologies, including acceptable ones. The use of (new) acceptable technologies leads to a lower number of perceived moral problems. However, the effect of using new technologies means that new moral problems are created. Because the number of values does not necessarily increase when openness to change is high, these new moral problems tend to remain unperceived. Overall, the total severity of moral problems (both perceived and unperceived) decreases as openness to change increases. This seems to suggest that the severity of these new (unperceived) moral problems is limited.

## Effect of value adaptation

The variable ‘propensity\_value\_adaptation’ determines how likely agents will choose to adapt values as a response to perceived moral concerns. Adapting values entails making values corresponding to the perceived moral problems more important. Doing so will prevent agents from choosing technologies that are likely to cause these moral problems, as these technologies become morally unacceptable.

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Figure : Effect of value adaptation on main output variables

Figure 4 shows the effect of value adaptation on main output variables. As expected, a high propensity\_value\_adaptation causes the number of values in the model to (slightly) increase. As agents rely more on values to cope with new moral problems, they tend to (relatively) rely less on innovation (i.e., the creation of new technologies). As can be seen in Figure 4, the number of technologies in the model decreases as value adaptation increase. Value adaptation has a strong effect on the number of unacceptable technologies found in the model. This is explained by the role of values in the model, which help to evaluate the acceptability of technologies. The higher the number of values in the model, the higher the number of unacceptable technologies is likely to grow.

## Effect of value dynamism

The variable ‘propensity\_value\_adaptation’ determines how likely agents will choose value dynamism as a response to perceived moral concerns. The variable ‘propensity\_value\_dynamism’ has a similar function as value adaptation, but the importance of values is only changed temporarily. After a certain amount of time, the importance of the value progressively decreases back to its initial value.

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Figure : Effect of value dynamism on main output variables

Figure 5 shows the effect of value adaptation on main output variables. The same effects on output variable can be perceived as for value adaptation, which is expected as both measures are similar. A slight difference can still be seen for the effect on the number of unacceptable technologies, which is less strong. The explanation is that values are only changed temporarily, which means that some technologies are only considered morally unacceptable for a limited amount of time. As a result, the average number of unacceptable technologies in the model is likely to be smaller.

## Effect of innovation

The variable ‘propensity\_innovation’ determines how likely agents will choose innovation as a response to perceived moral concerns. When choosing innovation, agent will try to create a new technology that is in line with values in the models. In line with values means that the new technology will not likely cause moral problems for which this value stands. Whether the agent is successful at creating this technology depends on a random distribution but is also depends on the openness to change of the society (the higher the openness to change, the higher the chance of successful innovation).

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Figure : Effect of innovation on main output variables

Figure 6 shows the effect of innovation on main output variables. In comparison to value adaptation and value dynamism, the effect of innovation seems to be stronger. As expected, a higher propensity for innovation leads to more technologies in the model, and less values. The number of unacceptable technologies in the model decreases, which seems to be the contrary effect as for value adaptation and value dynamism. One could suggest that innovation is more successful at coping with unacceptable technologies and moral problems, but the total severity of moral problems does not strongly decrease. A more convincing explanation is that values are required to judge upon the acceptability of technologies. In case there are less values in the model, the number of unacceptable technologies decreases as well while these technologies might still cause moral problems. Because of a lack of values, many moral problems also remain unperceived.

## Combined effect of value adaptation, value dynamism and innovation

In the sections above, we have studied the effect of value adaptation, value dynamism and innovation apart from each other. It is however likely that the combination of these actions may produce better results to prevent moral problems in society. Here, we explore the combined effect of the three variables at decreasing the severity of moral problems. This is done by performing a PRIM (Patient Rule Induction Method) experiment (Friedman and Fisher 1999), where the simulation model is run a high number of time, each time taking a different value for each input parameter. The experiment allows tracing which (combinations) of input parameters have led to a specific outcome of interest. We perform this experiment two times, one where needs in the model do not change, and one where they do.

### Simulation outputs (no change in needs over time)

Table 3 shows which ranges of input parameters have led to cases where the severity of moral problems was low and cases where it was high. Cases where the severity of moral problems was low were essentially observed when the propensity for value dynamism was high (between 0.49 and 1). Cases where the severity of moral problems was high were observed when, simultaneously, the propensity innovation was high, and the propensity for value adaptation and dynamism was low.

Table : Combined effect of input parameters on the severity of moral problems (no change in needs)

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| **Low severity** | A picture containing text, screenshot, rectangle, diagram  Description automatically generated |
| **High severity** | A picture containing text, screenshot, diagram, font  Description automatically generated |

The effect of value dynamism on low severity of moral problems can be explained by the fact that value dynamism is least about to cause technological change in the model. Choosing innovation might create new moral problems for which society does not have the right values. Temporarily changing values appears to be sufficient in cases needs are steady. On the contrary, the combination of high propensity for innovation and low value adaptation and value dynamism causes the most severe moral problems. Innovations causes new issues, which are then poorly addressed in cause the society is not able to create adequate values.

### Simulation outputs (changes in needs over time)

Table 4 shows the combined effect of value adaptation, value dynamism and innovation on the severity of moral problems, when needs of the society are changing over time. The severity of moral problems is low when the propensity for innovation is high and value adaptation is high (to a lower extent). The severity of moral problems is high when innovation is low.

Table : Combined effect of input parameters on the severity of moral problems (change in needs)

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| --- | --- |
| **Low severity** |  |
| **High severity** |  |

In comparison to simulation outputs with no change in needs, a high propensity for value dynamism does not necessarily lead to a low severity of moral problems. Rather, it is the combination of an innovation and value adaptation that allows a society to cope with changing needs. Here also, innovation is useful to create new technologies to respond to changing needs while value adaptation allows the adjustment of values. For case when the severity of moral problems is high, a combination of value adaptation, value dynamism and innovation does not seem to play a role anymore. In case innovation is low, society is not able to cope with changing needs, which results in strong moral problems.